LABORATOIRE
DE L'ACCÉLÉRATEUR
LINÉAIRE

Instrumentation for high energy physics

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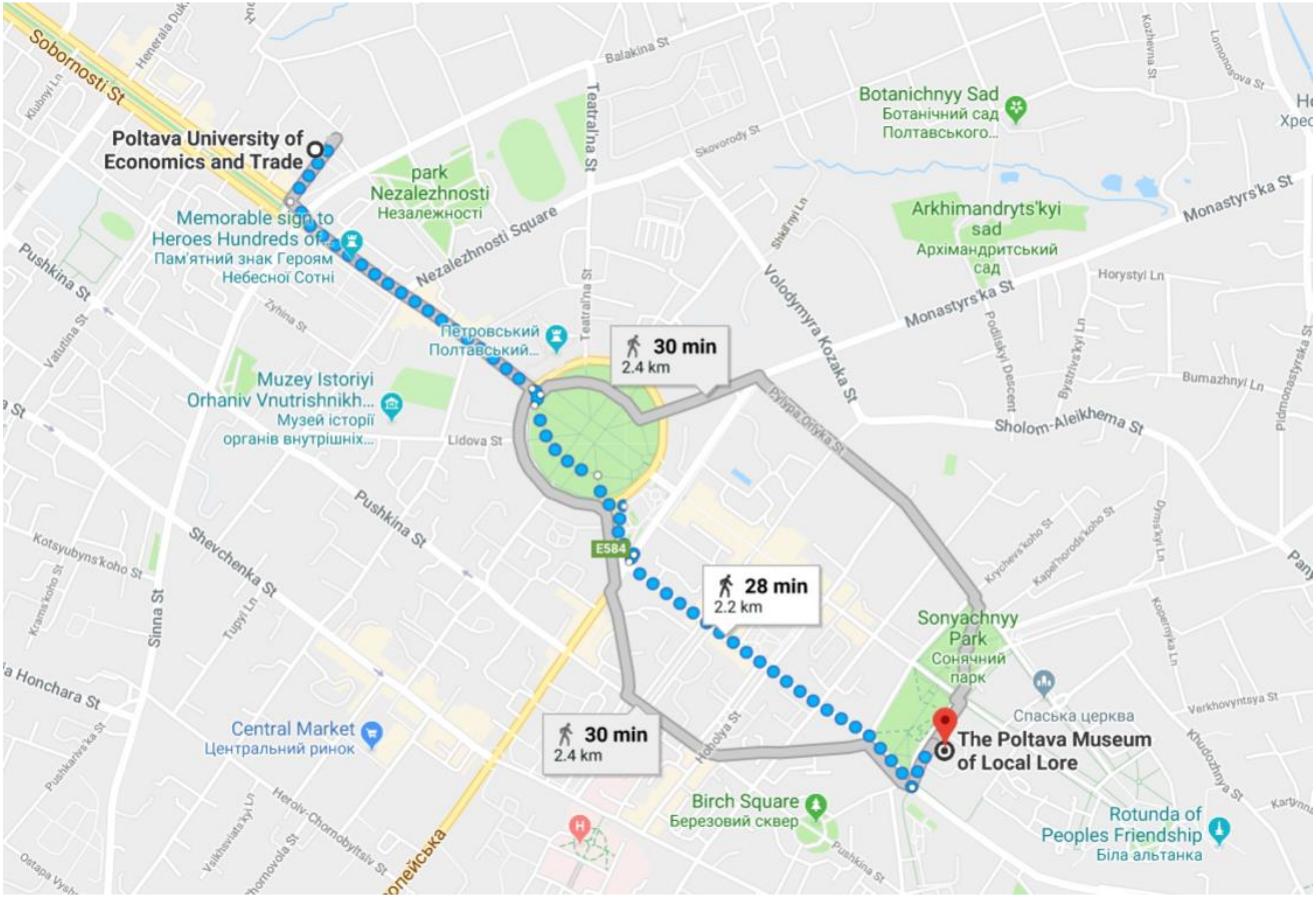
- ☐ Passage of particles through matter
- ☐ Photon detectors
- ☐ Scintillators
- ☐ Cherenkov light detectors, time-of-flight detectors
- ☐ Calorimeters
- ☐ **Tracking detectors: silicon and gaseous detectors, introduction**

- ☐ Very selective and personal, no way to cover all technologies/detectors
- ☐ Many simplifications, avoid formalism where possible
- ☐ No proper references to the origin for many plots

TESHEP, Poltava - Ukraine, 13-20/07/2018

Полтавський краєзнавчий музей

Полтавський краєзнавчий музей



Monday-Sunday 9-17, Wednesday closed

Gaseous detectors: examples

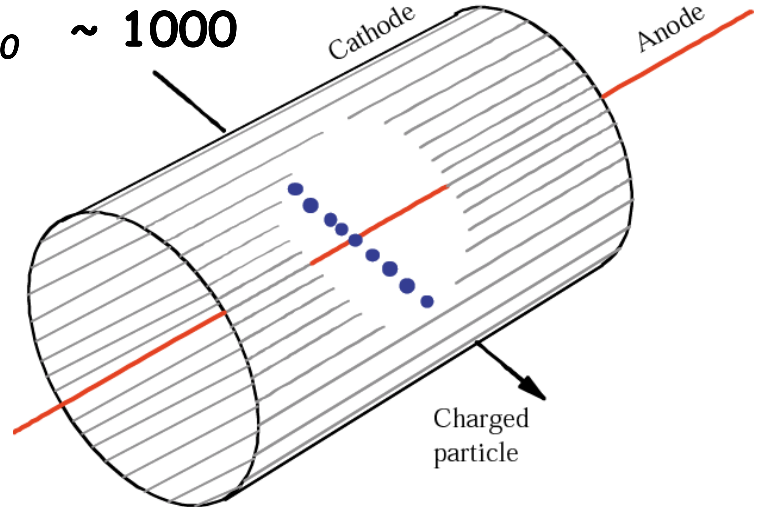
My first gaseous detector : Straw Tube

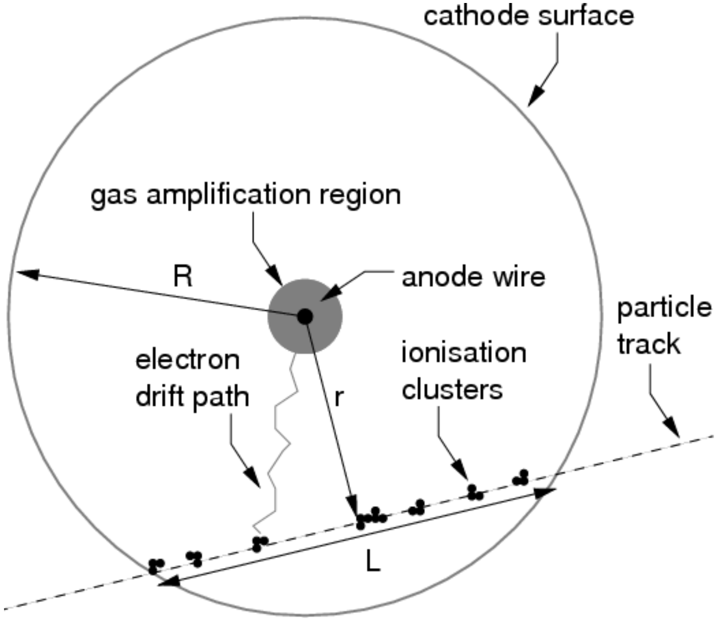
Cathode: A metallic cylinder of radius R

Anode: A gold plated tungsten wire of radius

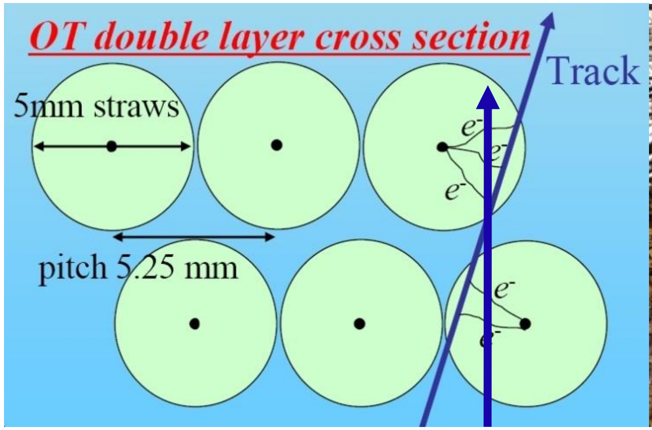
r_0 ~ 10 μm

R/r_0 ~ 1000



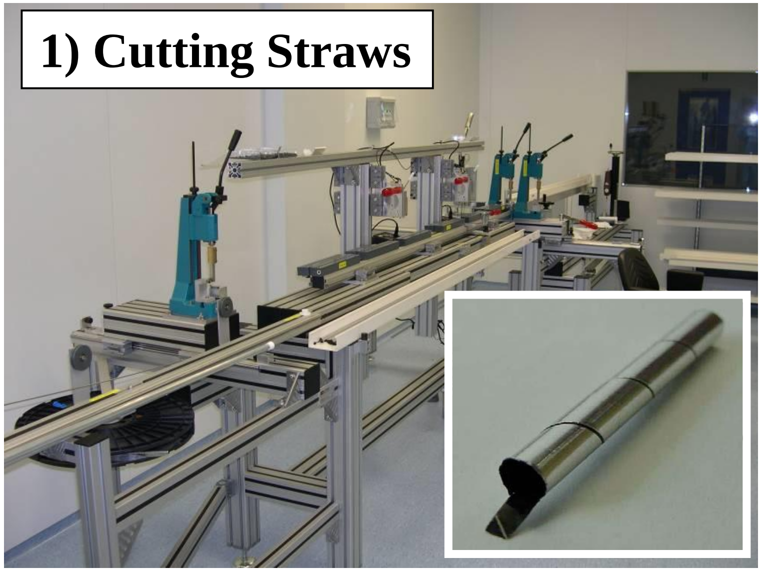


… and take MANY straws to have high efficiency.

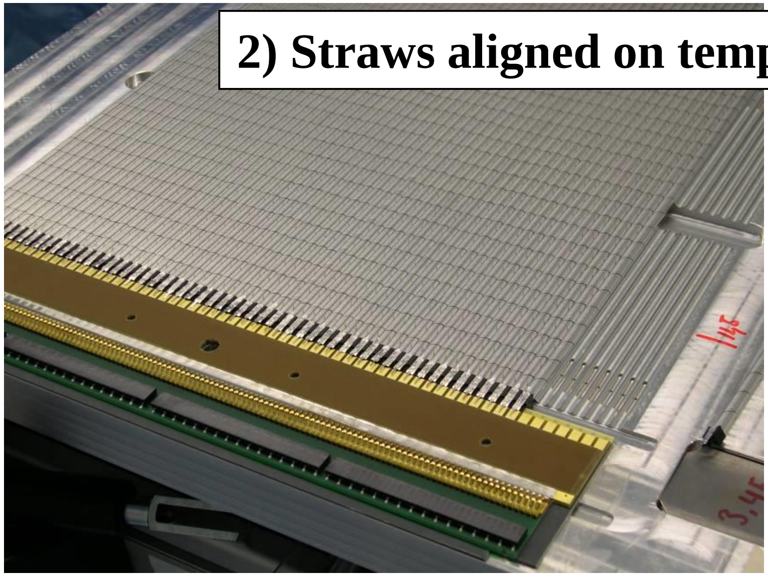


Q: How many space coordinates can you measure with a straw tube ? With which precision ?

Straw Tube : LHCb outer tracker

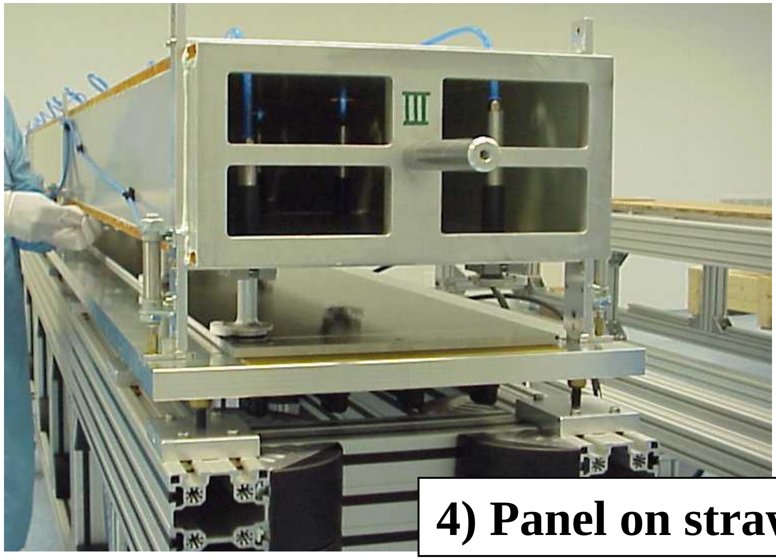


1) Cutting Straws

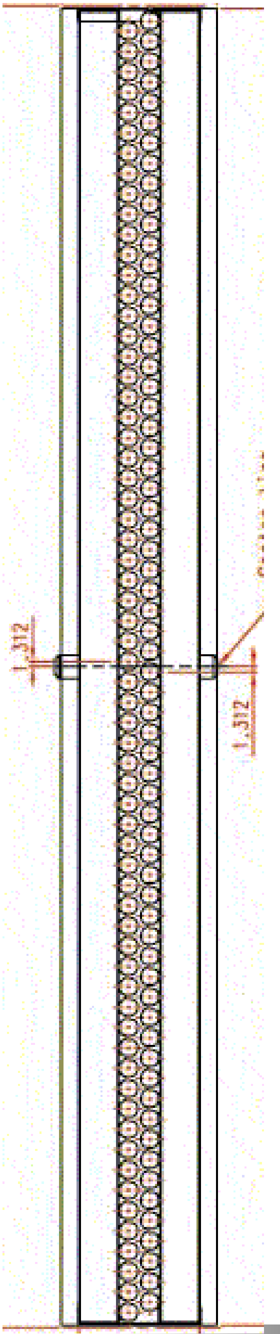


2) Straws aligned on template

3) Glue on panel



4) Panel on straws



Charged track passes through electric field

Primary Ek = 10 … 100 eV (then secondary) ionization $n_{total} \approx \times 3 \text{ or } \times 4 . n_{primary}$

Drift, electrons drift faster

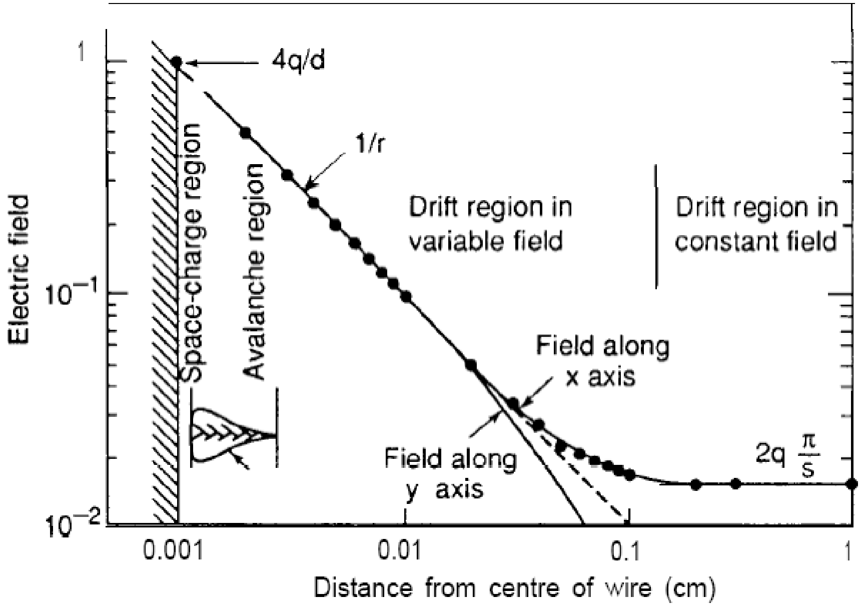
$$\frac{v_{electron}}{v_{ion}} \approx 10^3 \quad \text{in } CO_2 \text{ with } E = 10^4 \text{ V/cm}$$

Signal multiplication, Gain ~10^4

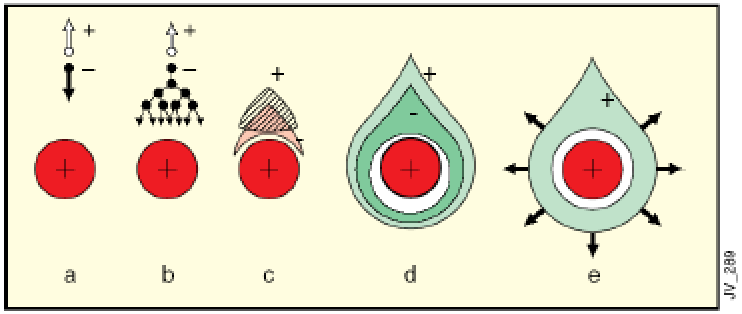
Signal collection

Avalanche development in high E field (~250 kV/cm) around a thin wire (multiplication region ~100 μm):

Georges Charpak, Nobel Lecture, December 8, 1992



Gas amplification next to anode wire

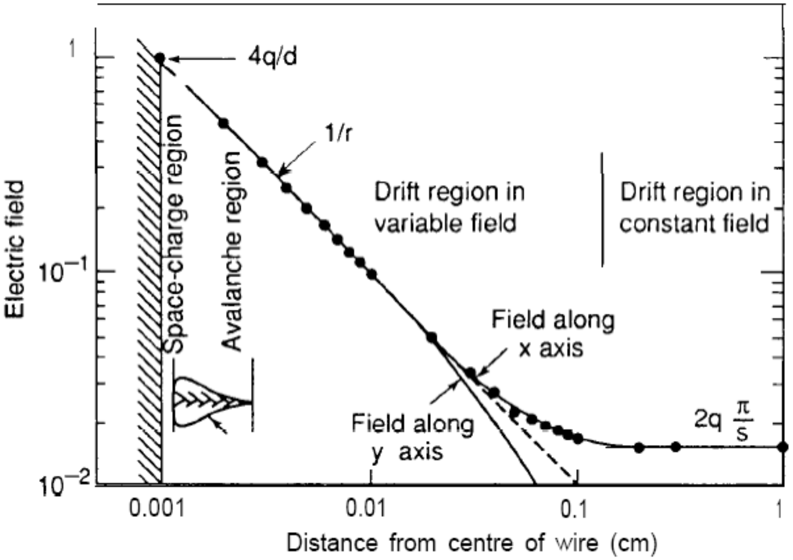


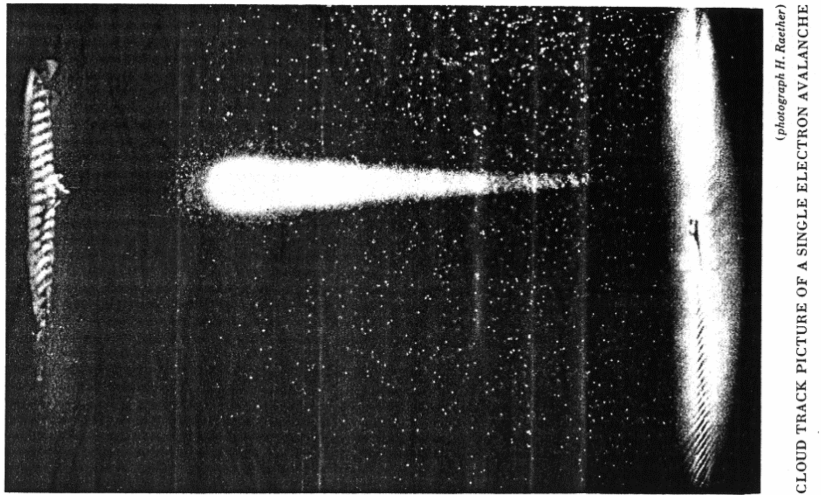
Fast signal induction during avalanche development → sub-ns RESOLUTION !

Q: Is it advantageous to multiplicate signal in a narrow region around the anode ?

Avalanche development in high E field (~ 250 kV/cm) around a thin wire (multiplication region ~100 μm):

Georges Charpak, Nobel Lecture, December 8, 1992

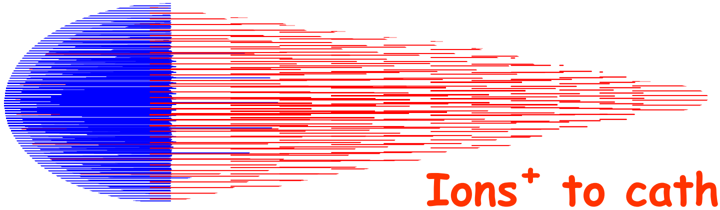



CLOUD TRACK PICTURE OF A SINGLE ELECTRON AVALANCHE (photograph H. Raether)

Cloud track picture of a single electron avalanche

Assuming that the total charge of the avalanche *Q* is produced at a (small) distance λ from the anode, the electron (q^-) and ion contributions (q^+) to the total induced signal ($q = q^- + q^+$) on anode are:

$$q^- = \frac{Q}{V_0}\int_a^{a+\lambda}\frac{dV}{dr}dr = -\frac{QC}{2\pi\varepsilon_0}\ln\frac{a+\lambda}{a} \ll q^+ = \frac{Q}{V_0}\int_{a+\lambda}^{b}\frac{dV}{dr}dr = -\frac{QC}{2\pi\varepsilon_0}\ln\frac{b}{a+\lambda}$$



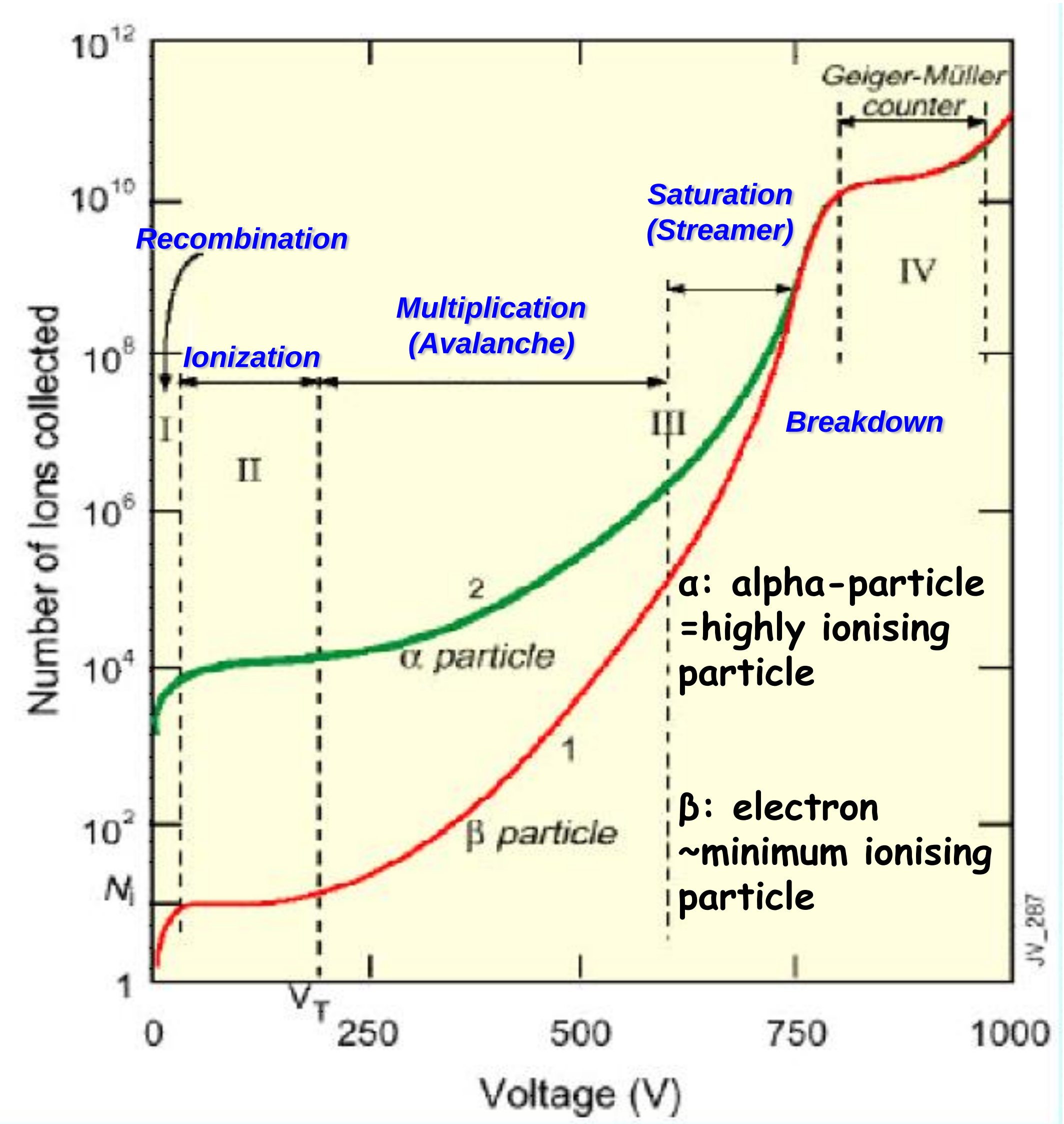
Electrons to anode (fast)

Ions$^+$ to cathode (slow)

But: use induced charge…

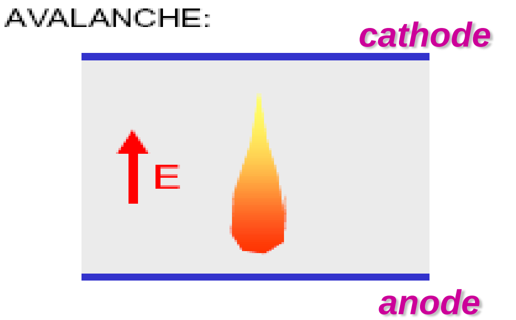
F. Sauli, http://www.cern.ch/GDD

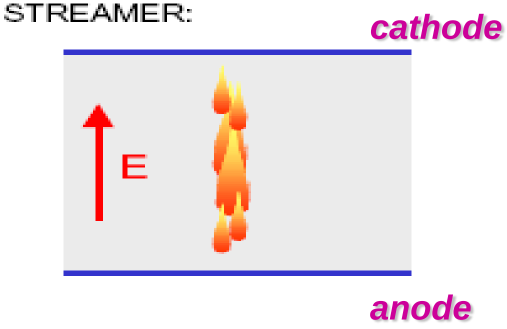
Gas amplification and the saturation effects.

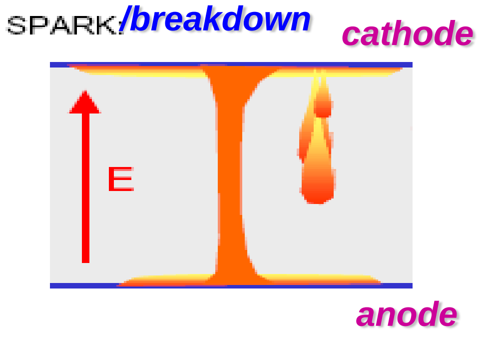


α: alpha-particle =highly ionising particle

β: electron ~minimum ionising particle







M. Titov

Multi Wire Proportional Chamber (MWPC)

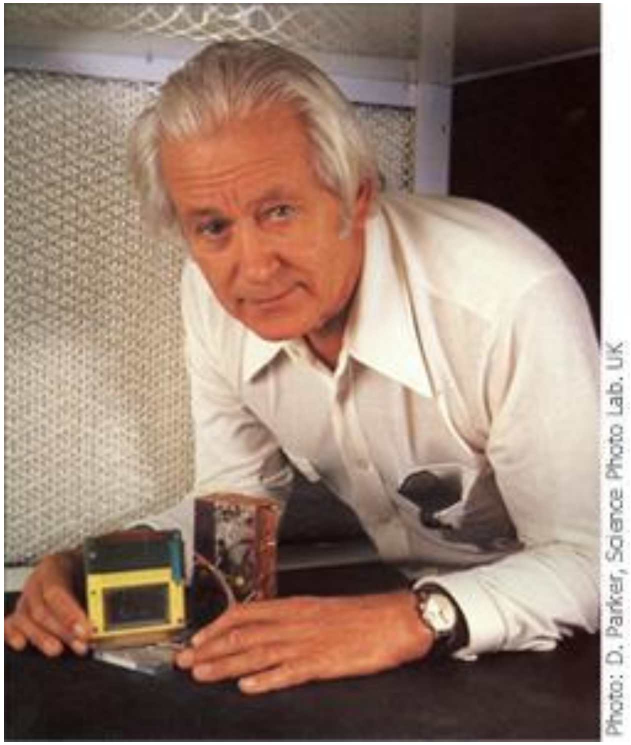


Photo: D. Parker, Science Photo Lab. UK

Transformed in high precision Drift Chambers (DC), Time Projection Chamber (TPC) etc.

Invented by Georges Charpak in 1968 …
… Nobel Prise in 1992

Applications :
X-ray and medical imaging, UV photon detection, neutron, and crystal diffraction and other material science studies, astronomy etc.

Radiography of Charpak's hand made with a digital X-ray imaging apparatus based on the MWPC

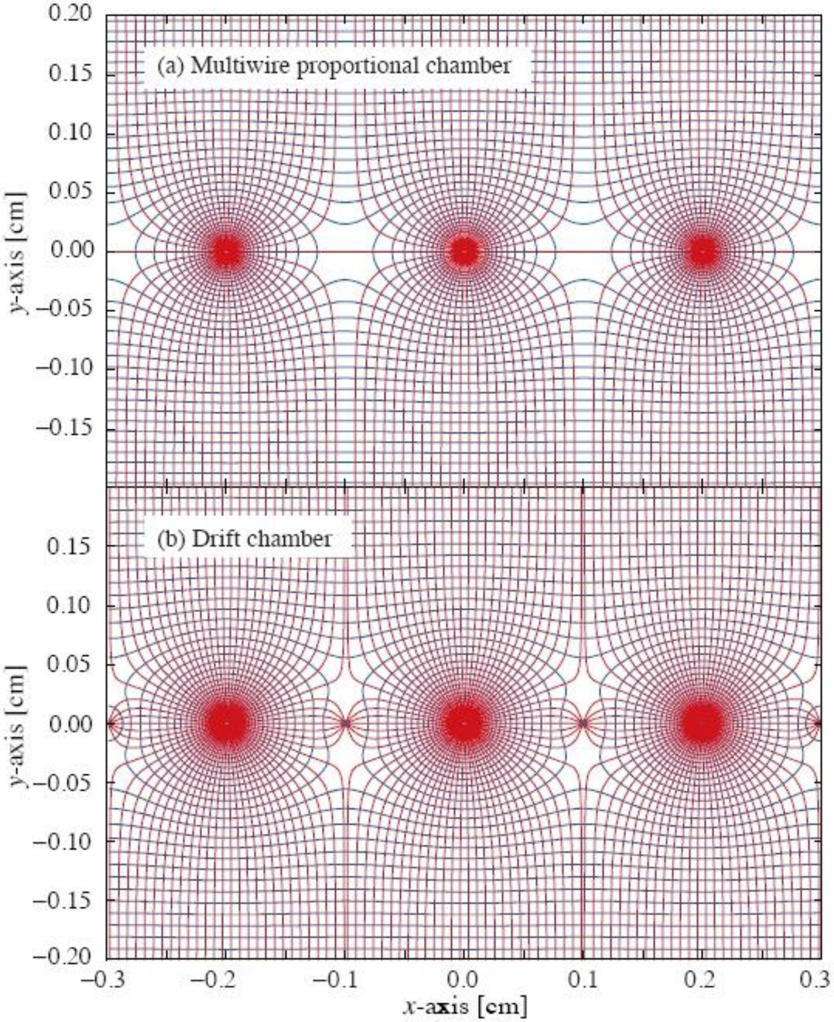


Figure 28.7: Electric field lines and equipotentials in (a) a multiwire proportional chamber and (b) a drift chamber.

Hexagonal drift cells formed by potential and sense wires (DC)

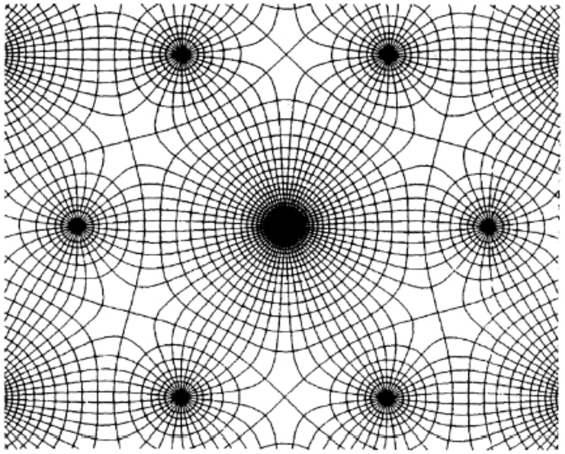
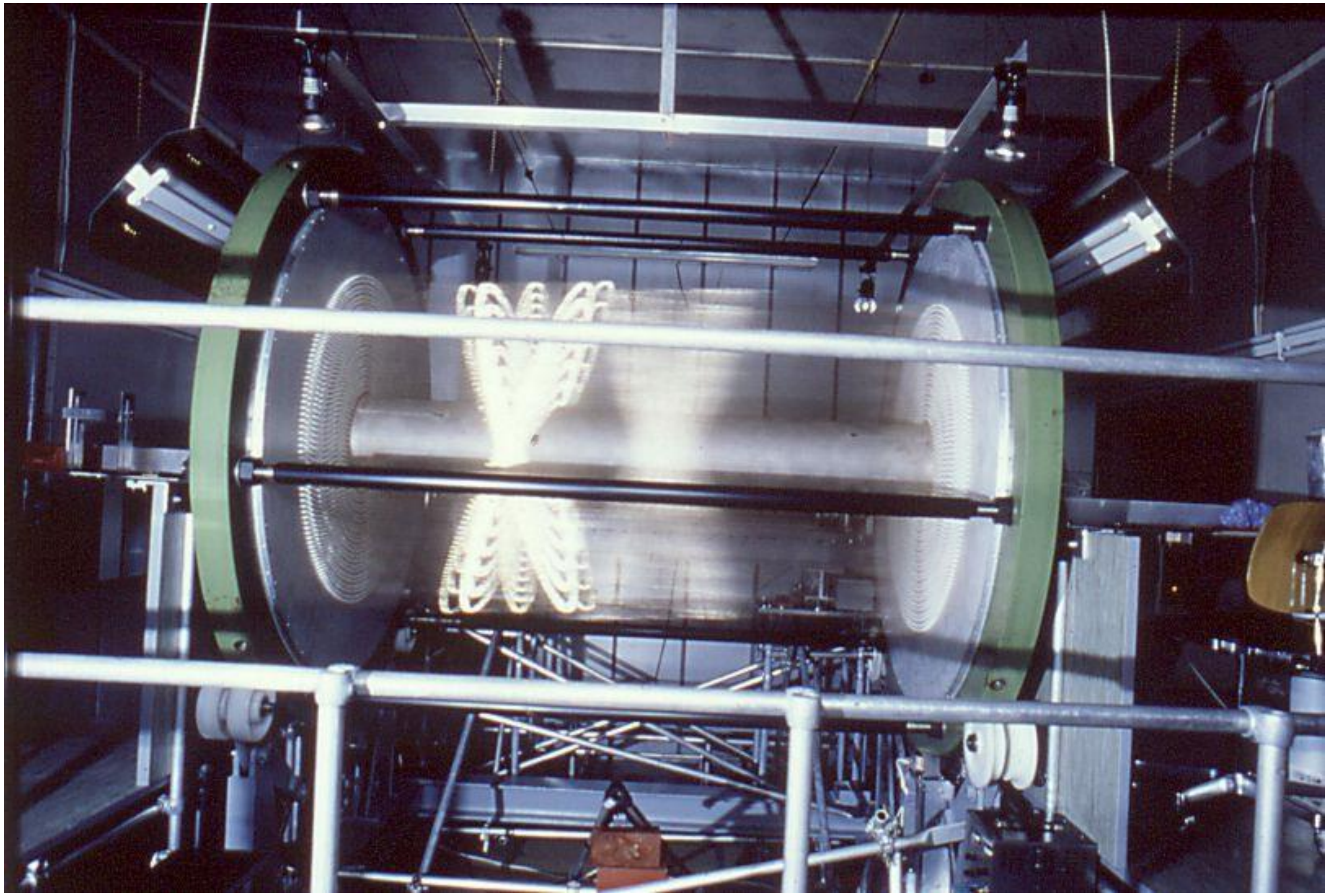


Figure 28.8: Electric field lines and equipotentials in a multiwire drift module. Each anode wire is surrounded by six cathode wires, and each cathode wire is surrounded by three anode wires.

ARGUS Drift Chamber



Hexagonal drift cells formed by potential and sense wires

Time Projection Chamber (TPC)

Large volume active detector.

full 3-D track reconstruction

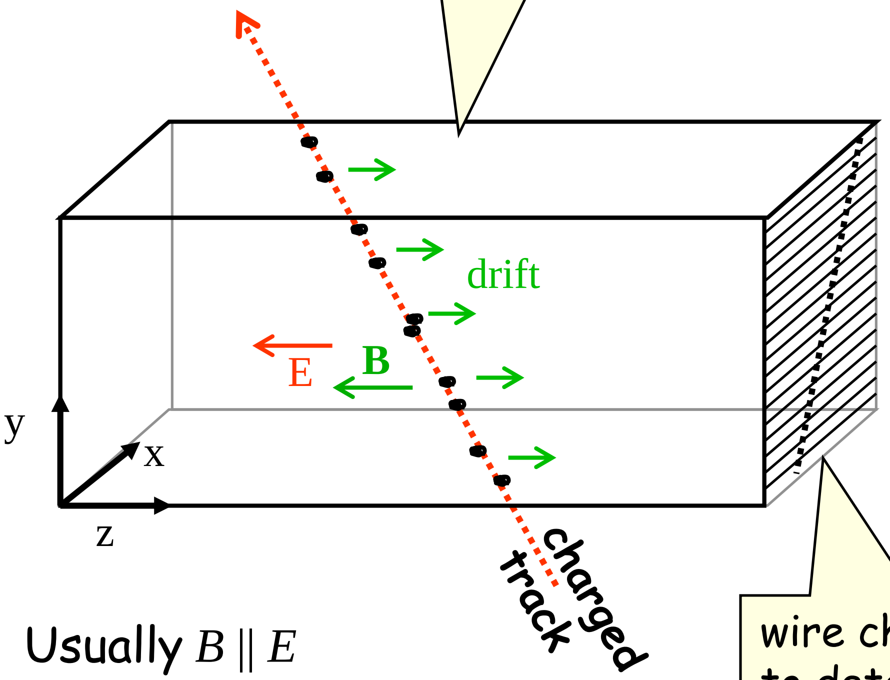
x-y from wires and segmented cathode

z from drift time

and

dE/dx

gas volume with E & B fields



wire chamber to detect projected tracks

Usually $B \parallel E$

Drift length ~ 1m

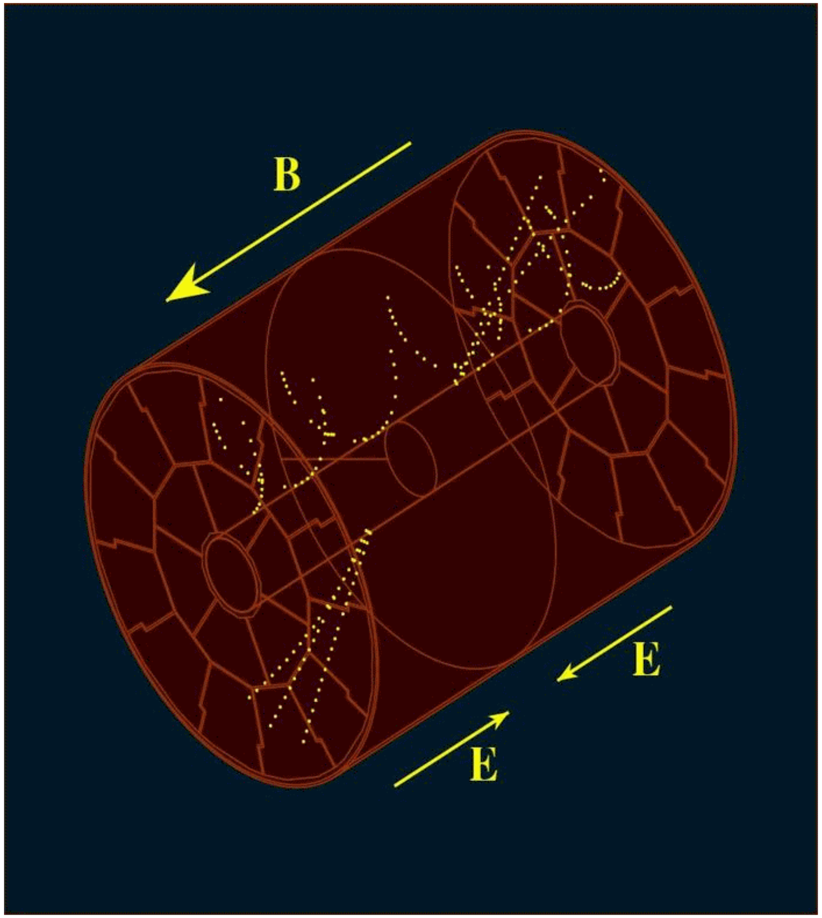
Rather stringent requirement on homogeneity of E and B

Space charge by ions

"Slow" detector $t_D \sim 10 .. 100\ \mu s$

… or R-O from both sides :

- ☐ Smaller drift distance
- ☐ Faster signal collection, smaller diffusion
- ☐ Less requirements to the electric field
- ☐ Better efficiency



… more difficult for high multiplicities …

Relativistic Heavy Ion Collider
at Brookhaven

High particle multiplicities
Low beam intensities

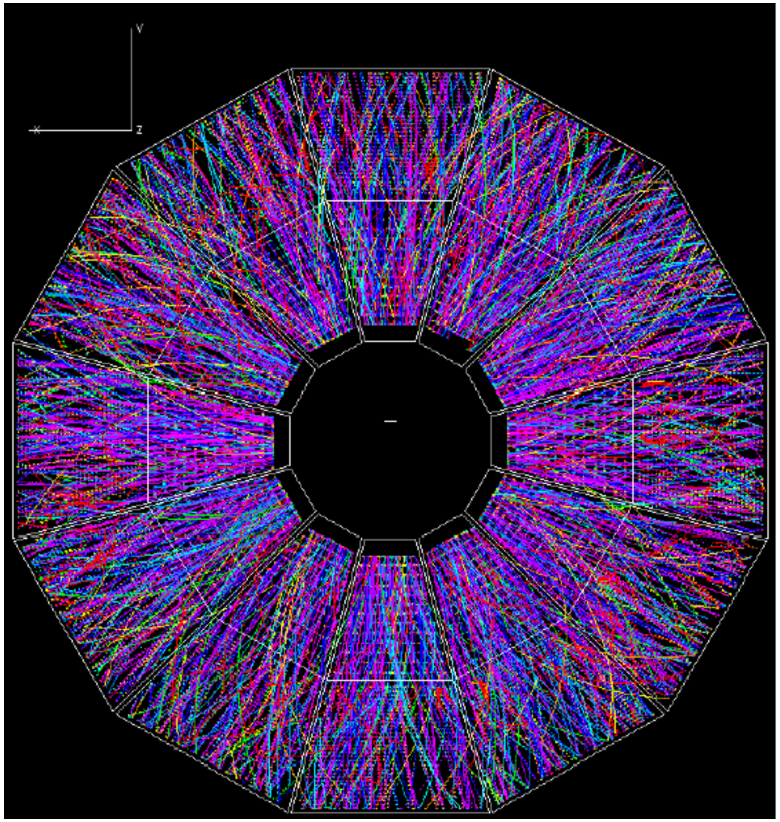
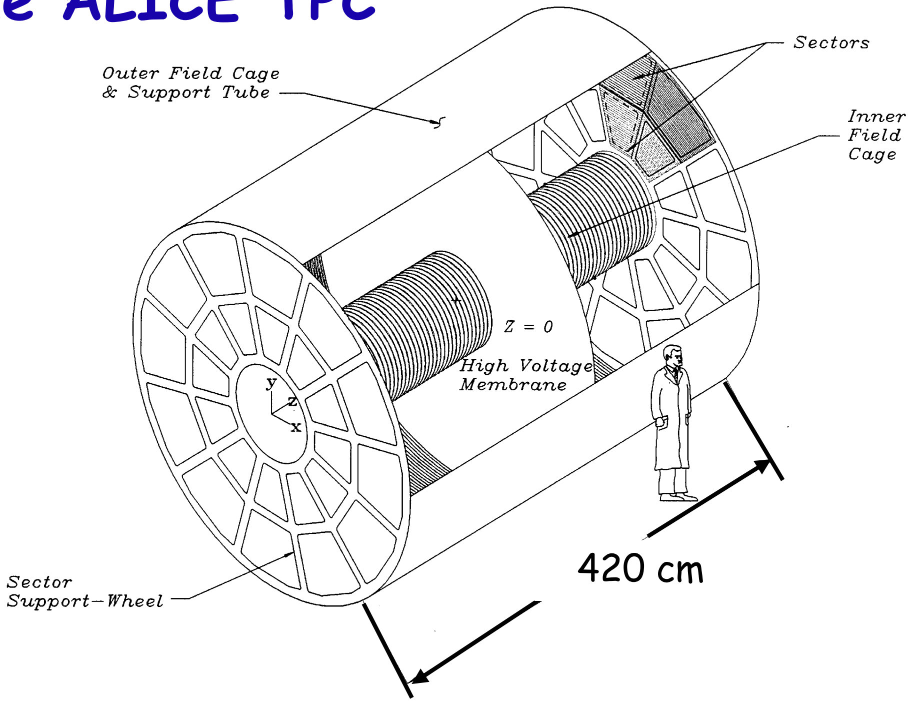
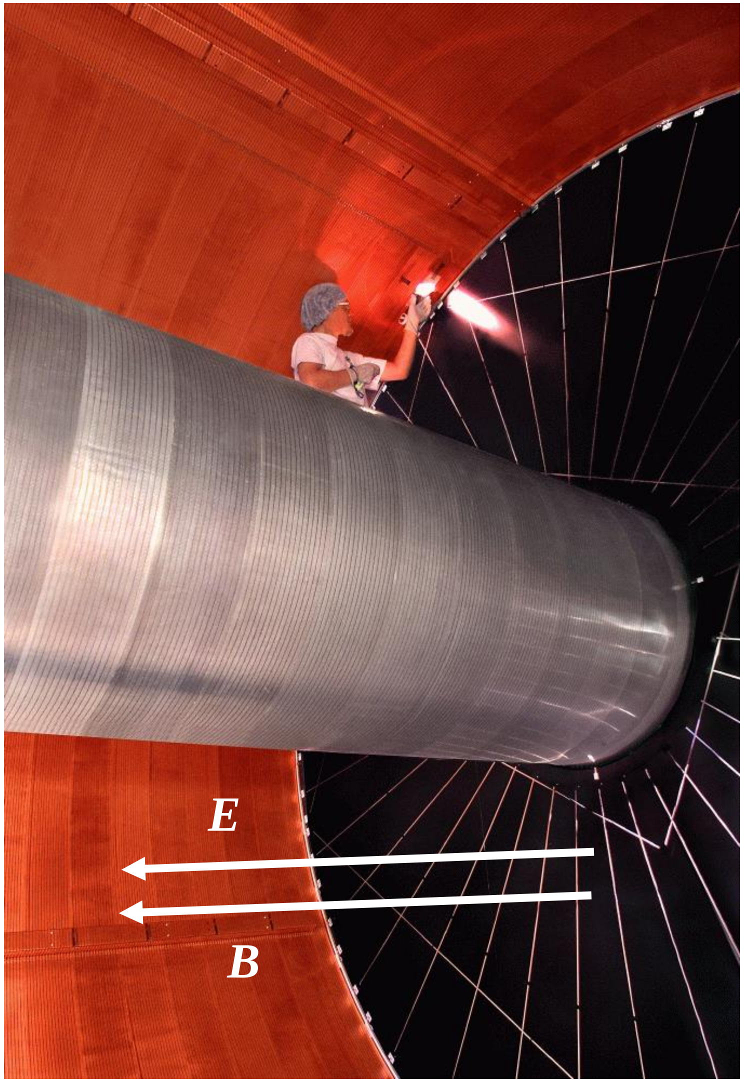


Image of Au-Au collision in STAR Time Projection Chamber (TPC)

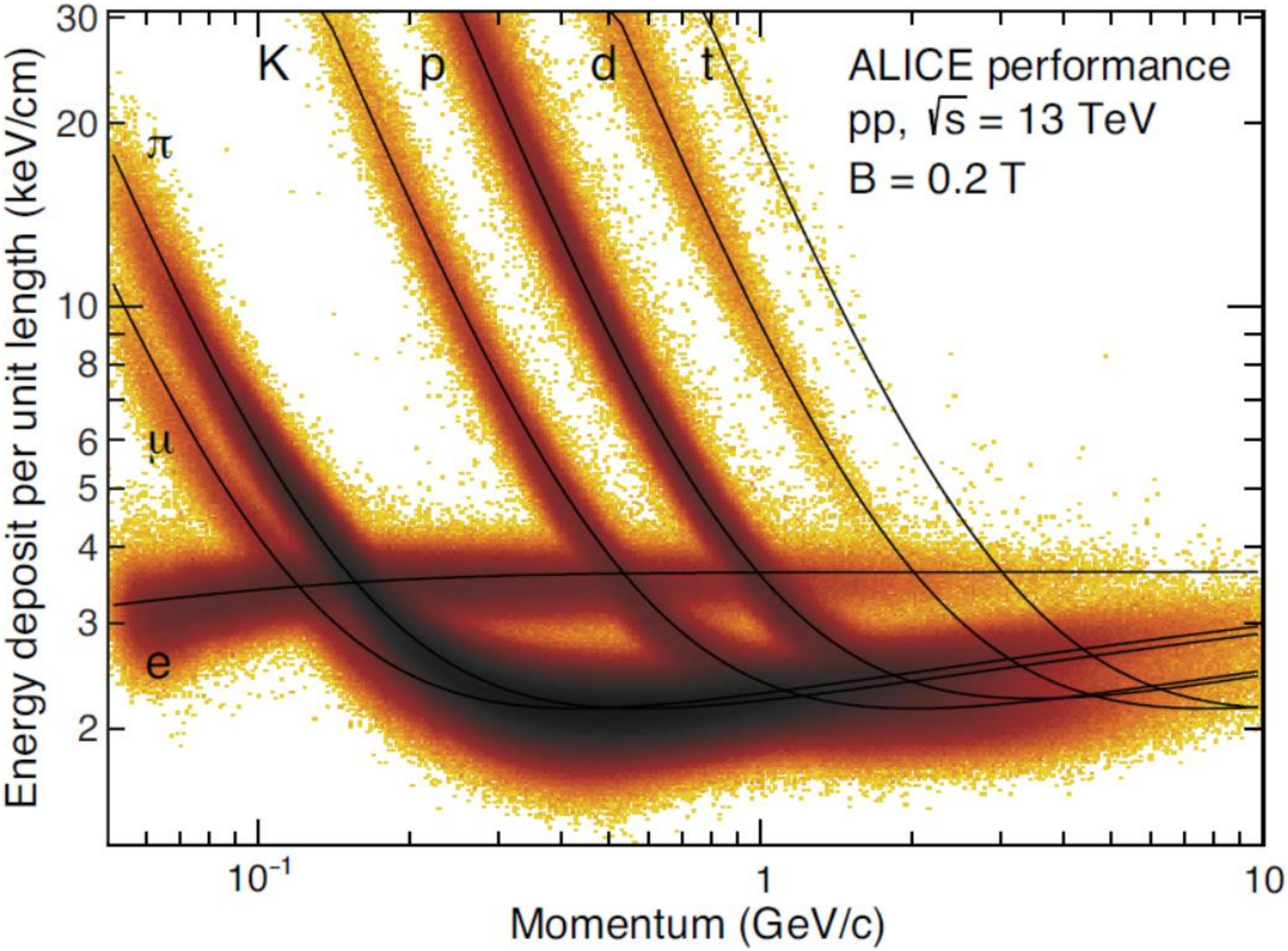
The ALICE TPC





← ALICE TPC field cage

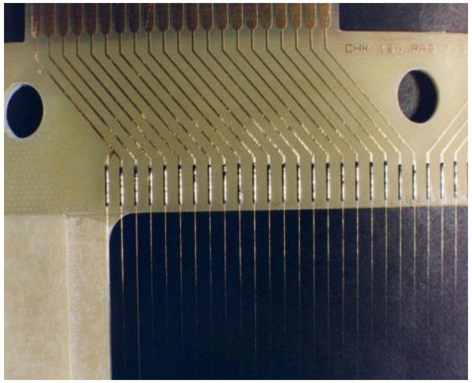
dE/dx with ALICE TPC

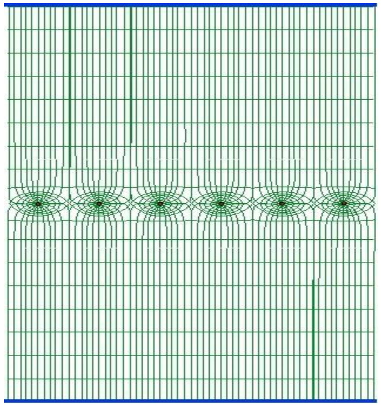


Micro-Pattern Gaseous Detector Technologies

Micro-Strip Gas Chamber (MSGC): thin anode and cathode strips on insulating support

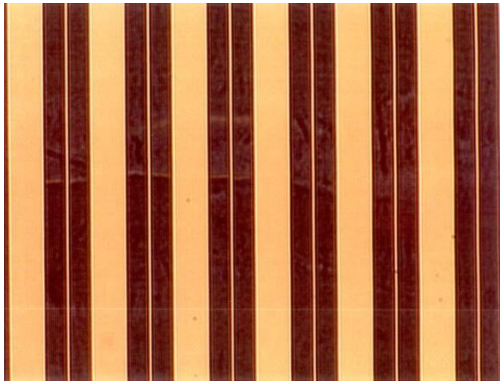
MWPC

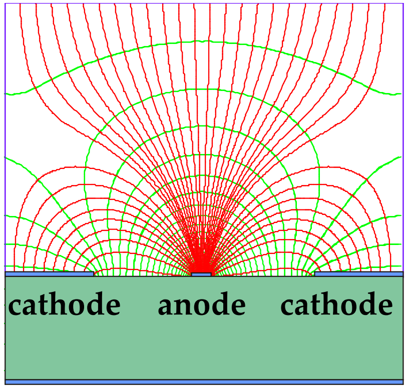




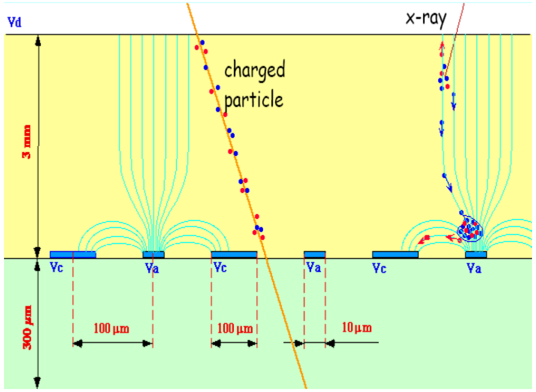
Typical distance between wires limited to 1 mm due to mechanical and electrostatic forces

MSGC

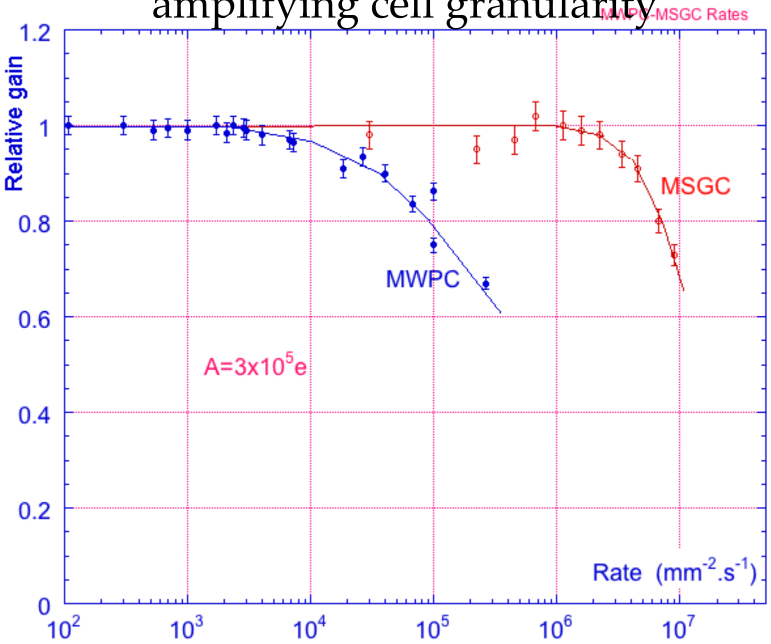




Typical distance between anodes 200 mum thanks to semiconductor etching technology



Rate capability limit due to space charge overcome by increased amplifying cell granularity



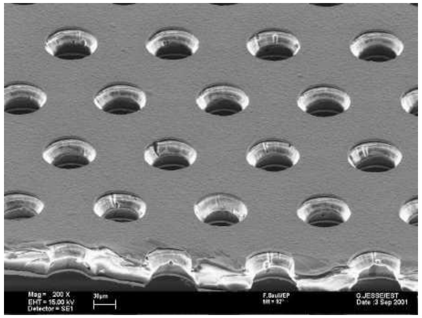
A. Oed, NIM A263 (1988) 351.

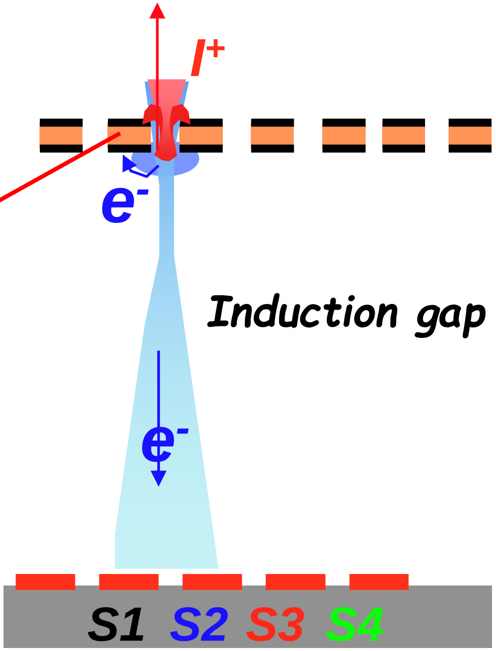
But discharges !

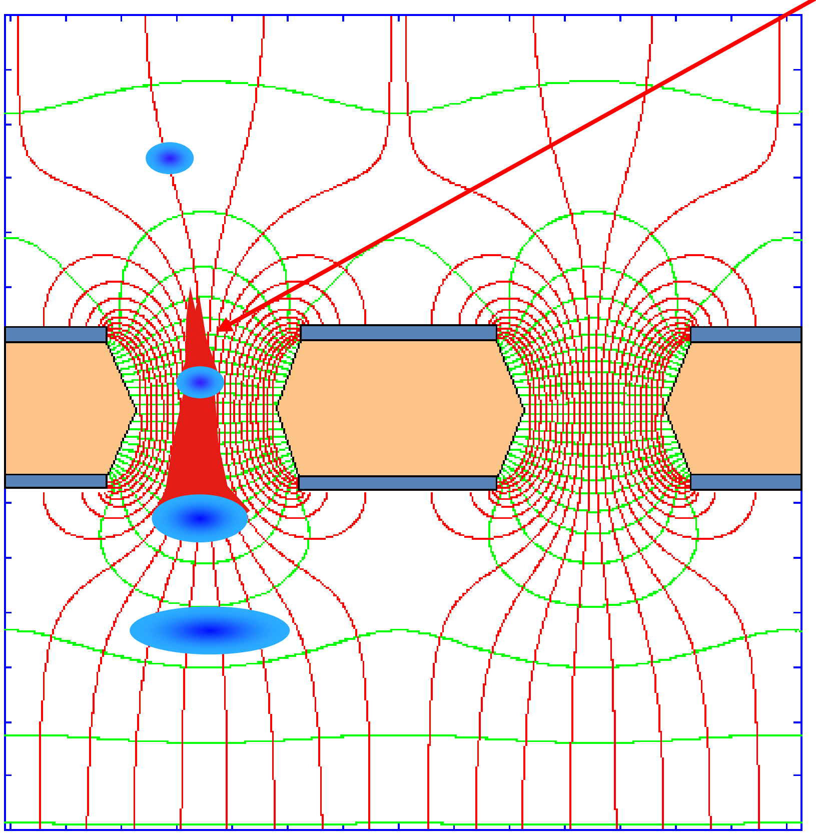
Gas Electron Multiplier (GEM)

- Thin metal-coated polymer foil chemically pierced by a high density of holes
- Thickness ~ 50 mum, hole diameter ~ 70 mum, pitch ~140 mum
- A difference of potentials between the two GEM electrodes ~ 500V
- Primary electrons released by ionizing particle, drift towards the holes, where high electric field triggers electron multiplication process.

F. Sauli, 1995





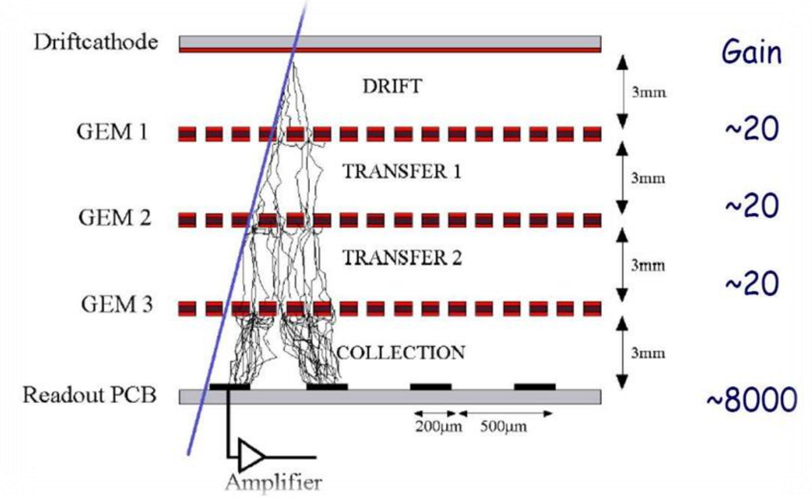


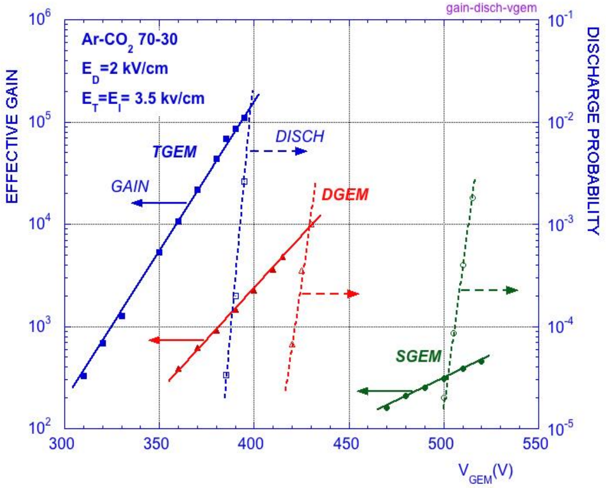
- Electrons collected on patterned readout board
- Fast signal can be detected on lower GEM electrode for trigger or energy discrimination
- All readout electrodes are at ground potential

F. Sauli, NIM A386(1997)531
F. Sauli, http://www.cern.ch/GDD

Triple Gas Electron Multiplier (GEM)

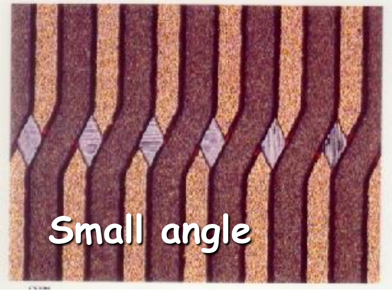
- ❑ Full decoupling of amplification stage (GEM) and readout stage (PCB, anode)
- ❑ For the same gain the discharge probability in a multi GEM configuration is much smaller.

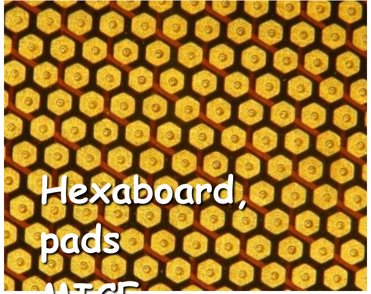




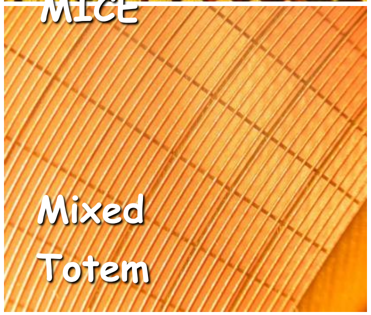

Cartesian

Compass, LHCb


Small angle

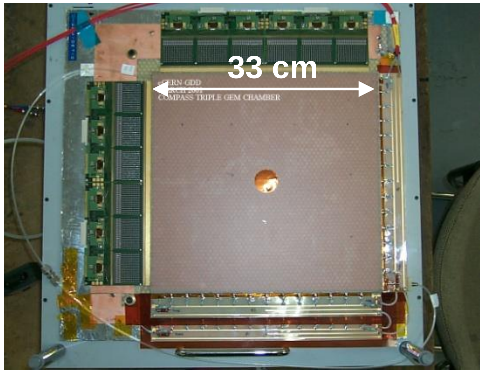

Hexaboard, pads

MICE


Mixed

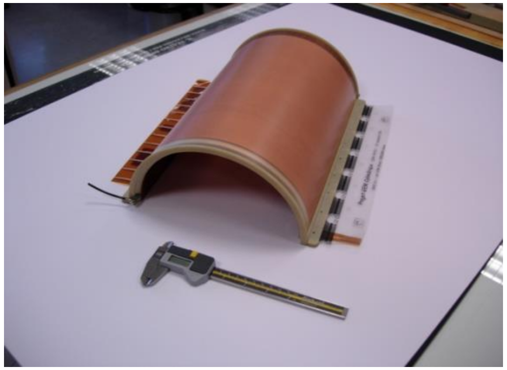
Totem

Amplification and readout structures can be optimized independently !



Compass

Totem



NA49-future

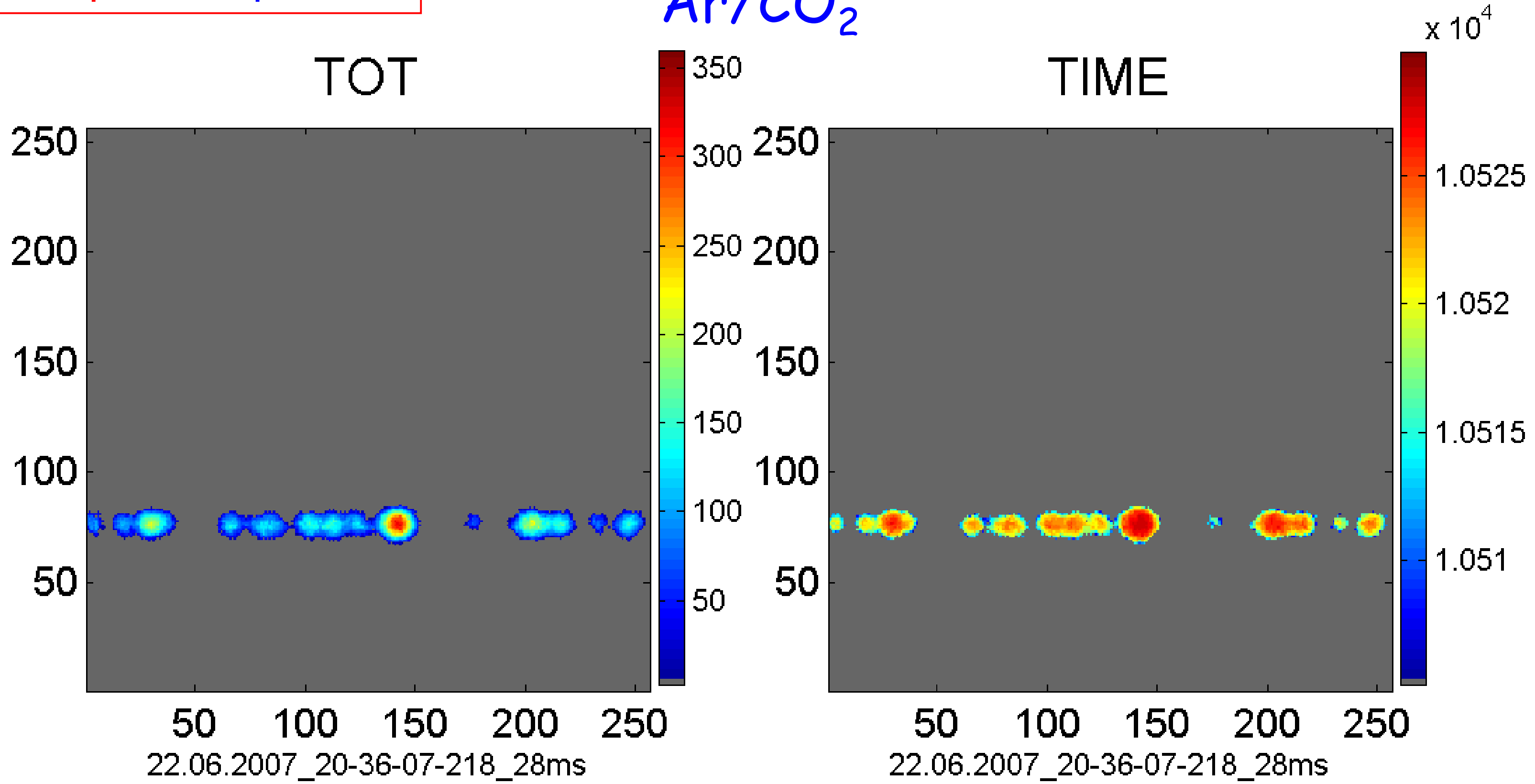
Electron tracks parallel to the cathode plane, passing between cathode and GEM1

RO with TIMEPIX

DESY e-beam

24x28mm^2 GEMs
with 50µm hole pitch

Ar/CO$_2$

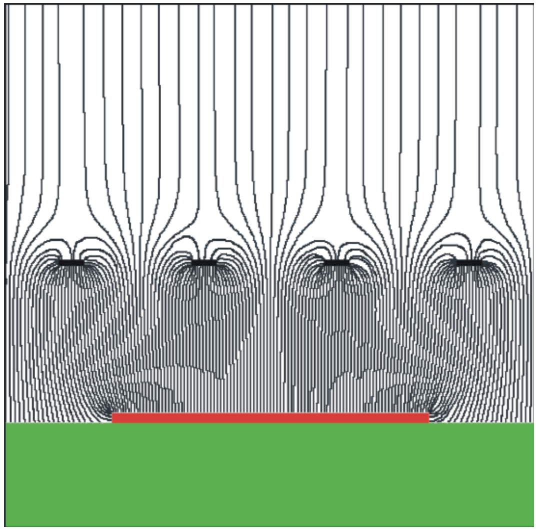


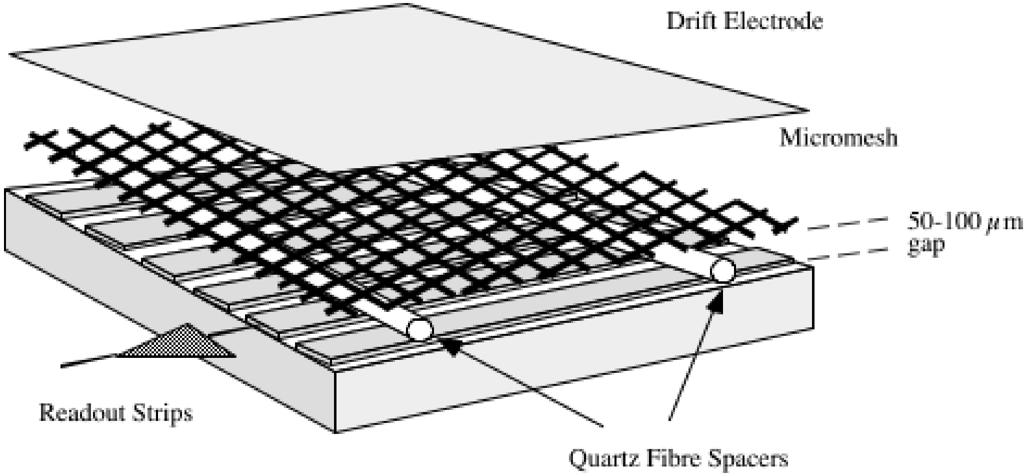
M. Titov

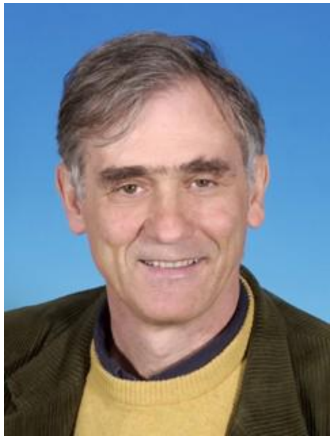
- Use time over threshold (TOT) information for clustering
- Gain with small pitched GEMs at $\Delta V_{GEM} \approx 346V$ comparable to $\Delta V_{GEM} \approx 403V$ with standard GEMs.

MICROMEsh GAseous chamber (MICROMEGAS)

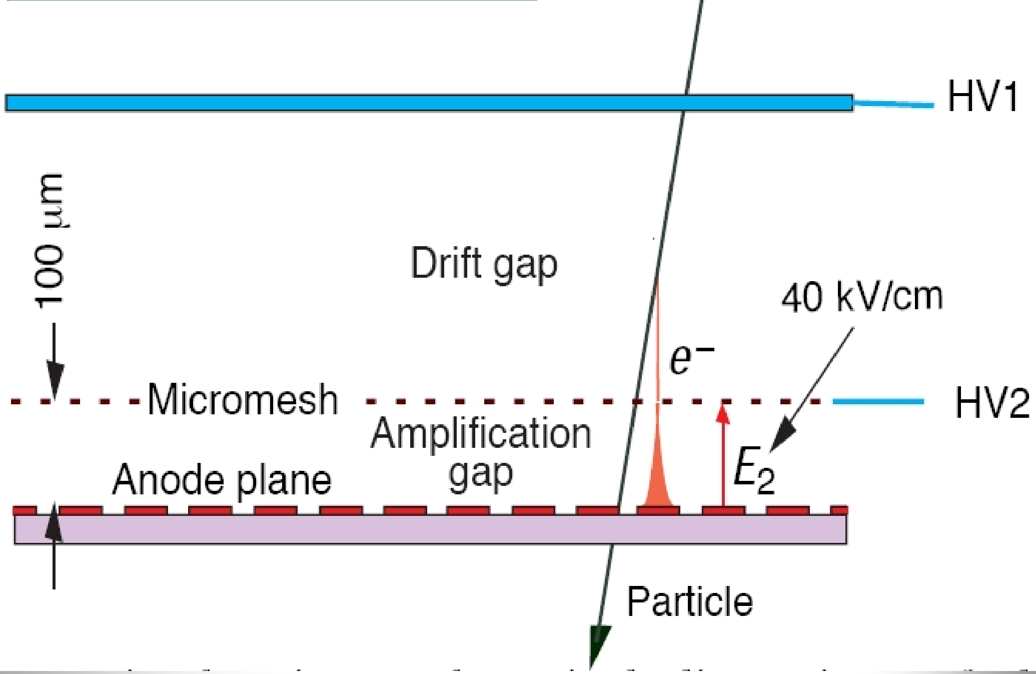
- ❑ Parallel plate multiplication in thin gaps between a fine mesh and anode plate

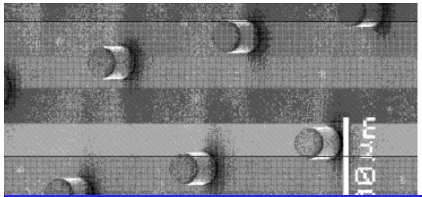




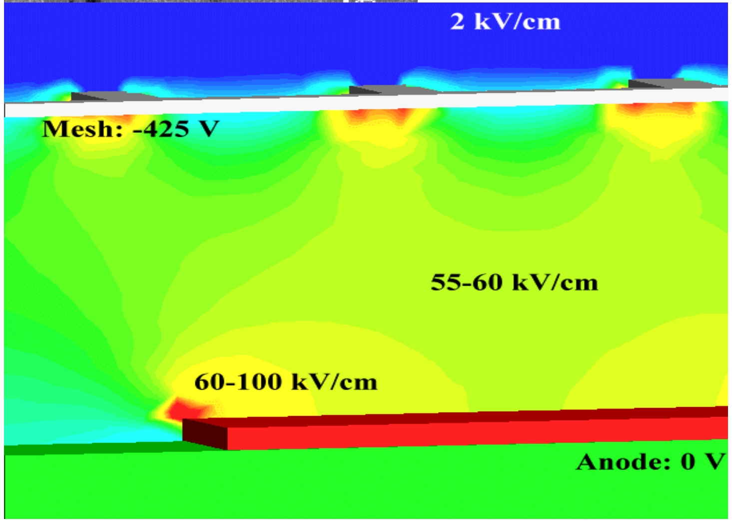


Giomataris, 1996





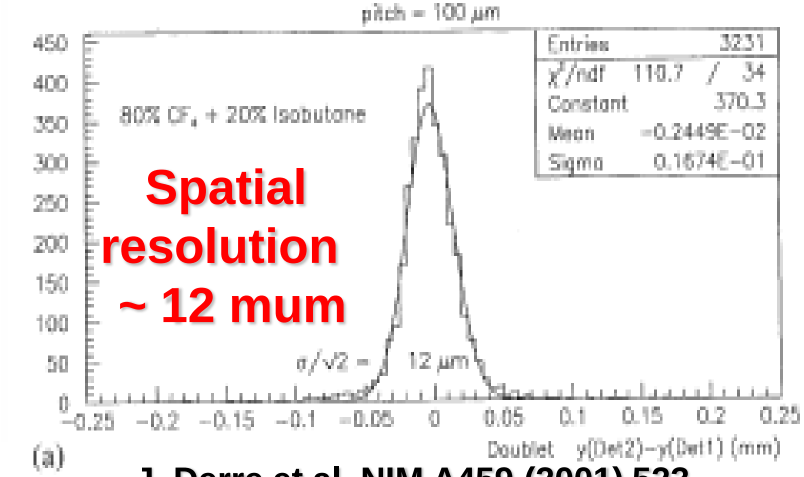
… or 50μm pillars



MICROMEsh GAseous chamber (MICROMEGAS)

Y. Giomataris,
NIM A376(1996) 29

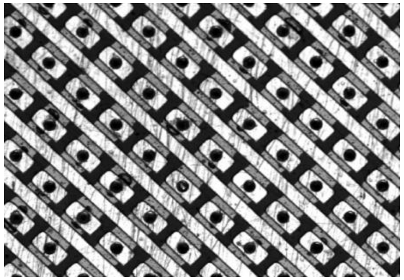
Small gap→ good energy resolution



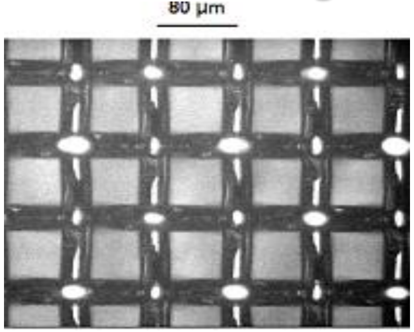
Spatial resolution ~ 12 mum

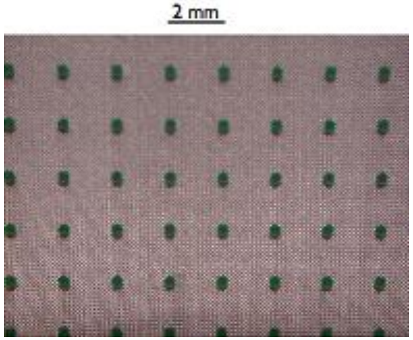
J. Derre et al, NIM A459 (2001) 523

CAST readout:



"Bulk" Micromegas:





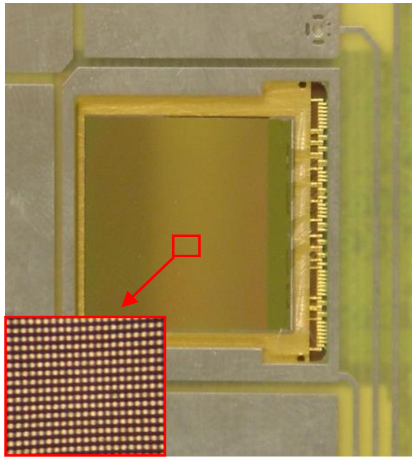
T2K Micromegas:

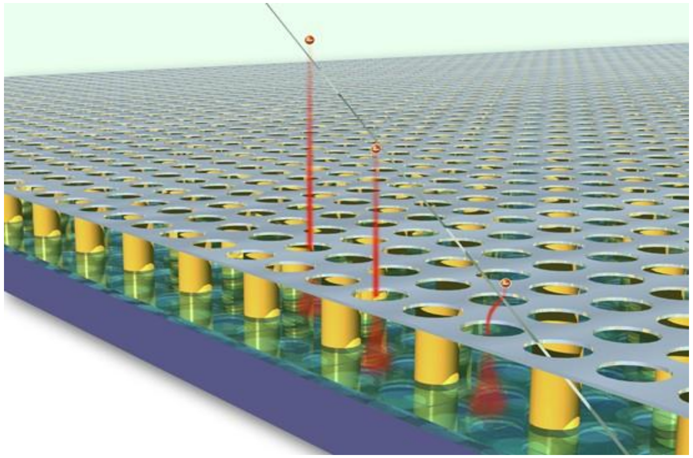
Piccolo Micromegas in Casaccia Reactor

Integrated electronics: pixel readout of MPGD

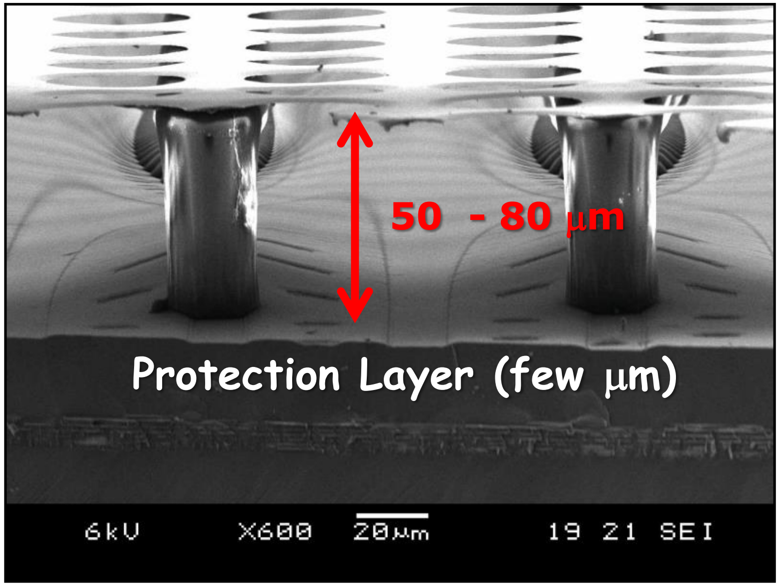
- **"InGrid" Concept**: By means of advanced wafer processing-technology INTEGRATE MICROMEGAS amplification grid directly (protection layer) on top of CMOS ("Timepix") ASIC
- **3D Gaseous Pixel Detector** → 2D (pixel dimensions) x 1D (drift time)

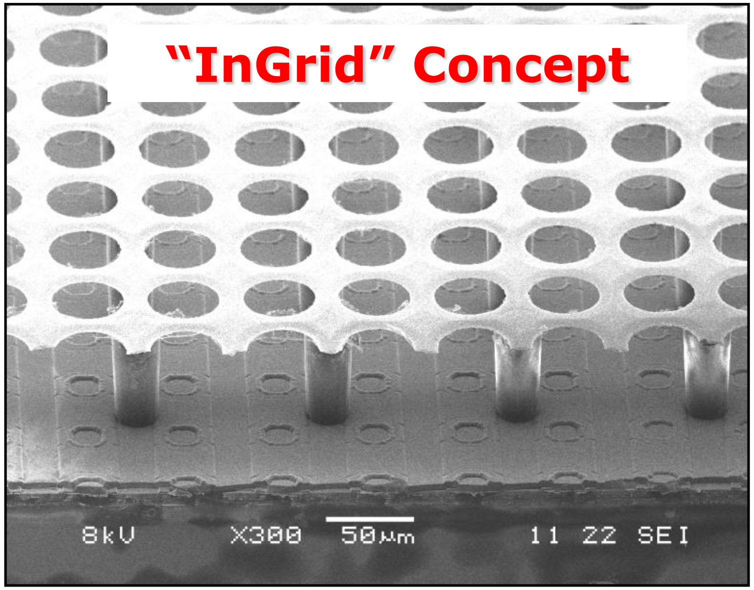
- Bump bond pads for Si-pixel
- Detectors - Timepix or Medipix2 (256 × 256 pixels of size 55 × 55 μm2) serve as charge collection pads.





- Each pixel can be set to:
  - TOT ≈ integrated charge
  - TIME = Time between hit and shutter end





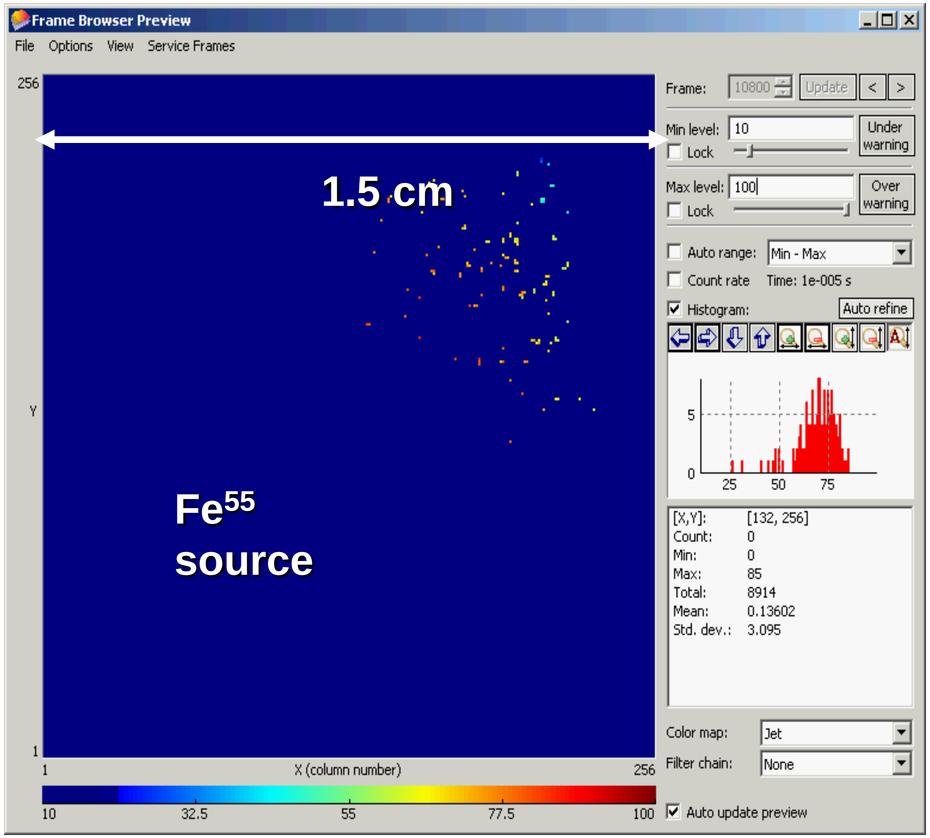
"InGrid" Detector: Single Electron Response and Discharges

Observe electrons from an X-ray (5.9 keV) conversion one by one and count them in micro-TPC (6 cm drift)

→ Study single electron response

Provoke discharges by introducing small amount of Thorium in the Ar gas - Thorium decays to Radon 222 which emits 2 alphas of 6.3 & 6.8 MeV

→ Round-shape images of discharges

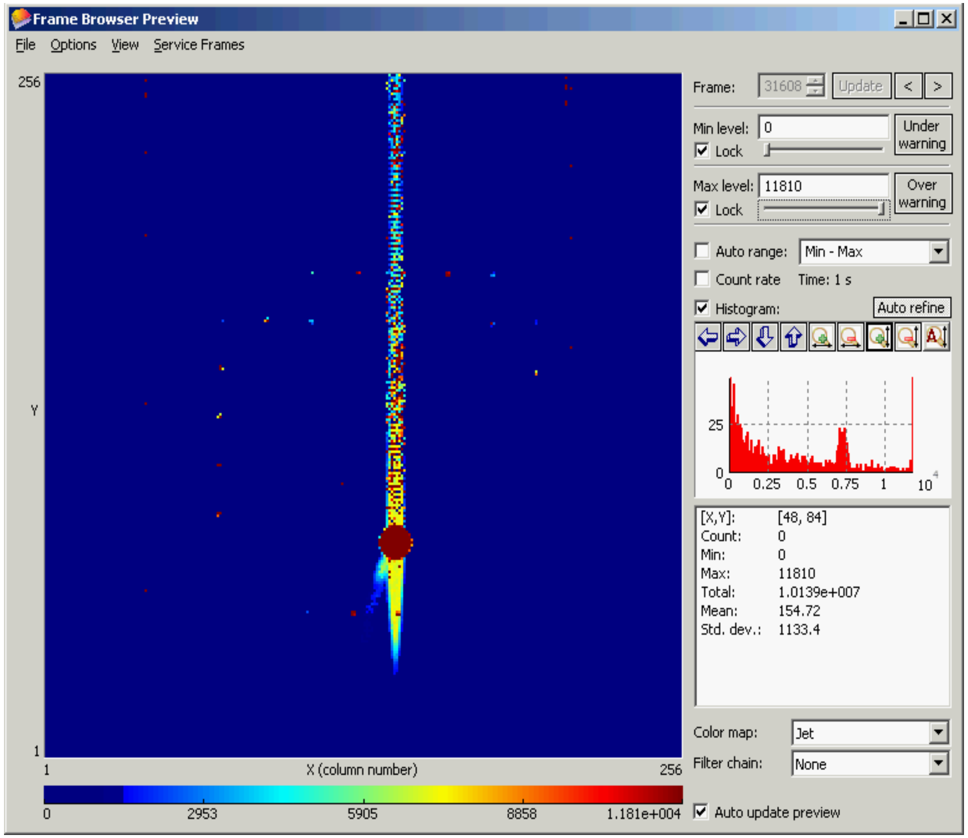


Frame: 10800
Min level: 10
☐ Lock
Max level: 100
☐ Lock
☐ Auto range: Min - Max
☐ Count rate Time: 1e-005 s
☑ Histogram:

[X,Y]: [132, 256]
Count: 0
Min: 0
Max: 85
Total: 8914
Mean: 0.13602
Std. dev.: 3.095

Color map: Jet
Filter chain: None
☑ Auto update preview

P. Colas, RD51 Collab. Meet., Jun.16-17, 2009, WG2 Meeting



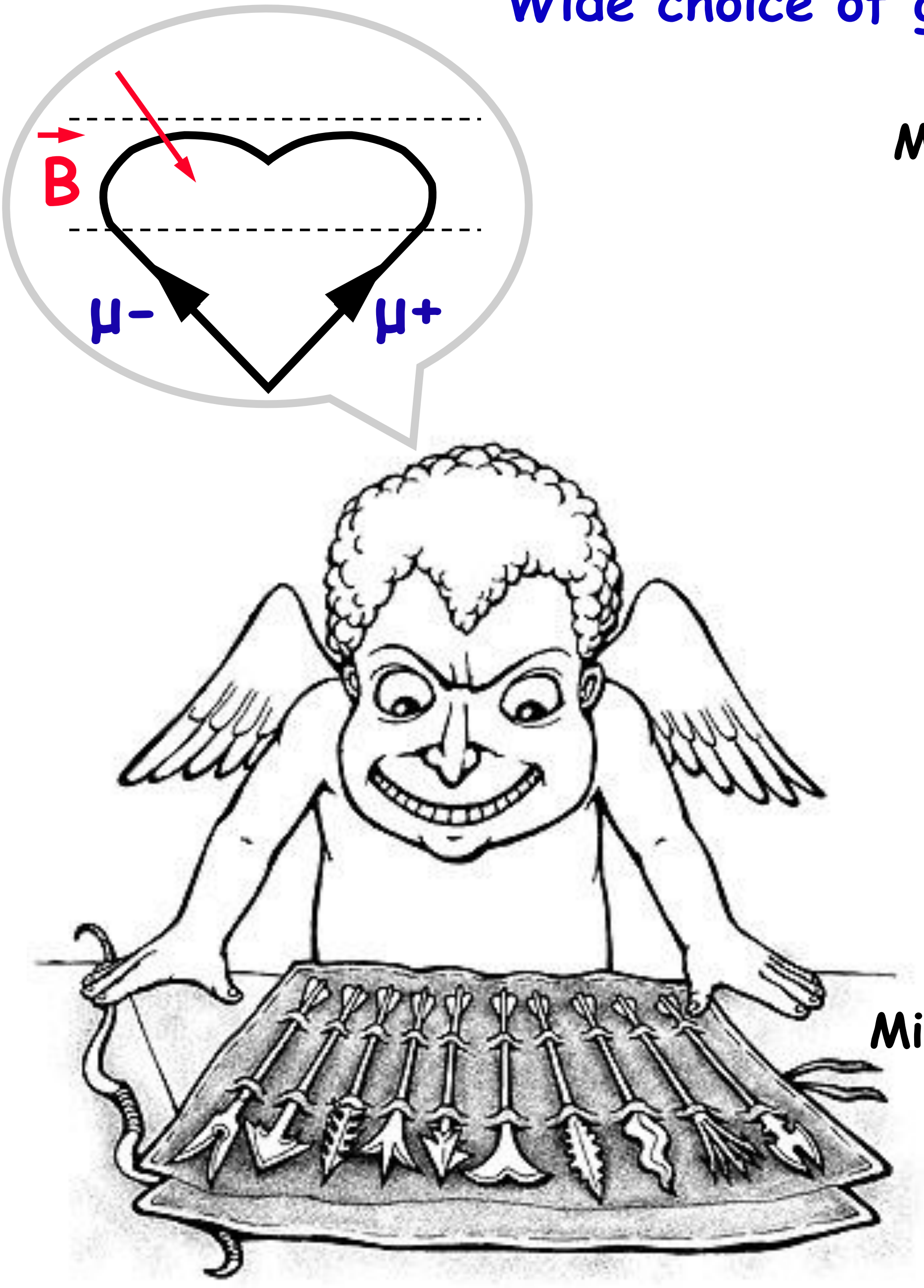
Frame: 31608
Min level: 0
☑ Lock
Max level: 11810
☑ Lock
☐ Auto range: Min - Max
☐ Count rate Time: 1 s
☑ Histogram:

[X,Y]: [48, 84]
Count: 0
Min: 0
Max: 11810
Total: 1.0139e+007
Mean: 154.72
Std. dev.: 1133.4

Color map: Jet
Filter chain: None
☑ Auto update preview

M. Fransen, RD51 Collab. Meet., Oct.13-15, 2008, WG2 Meeting

Wide choice of gaseous detectors

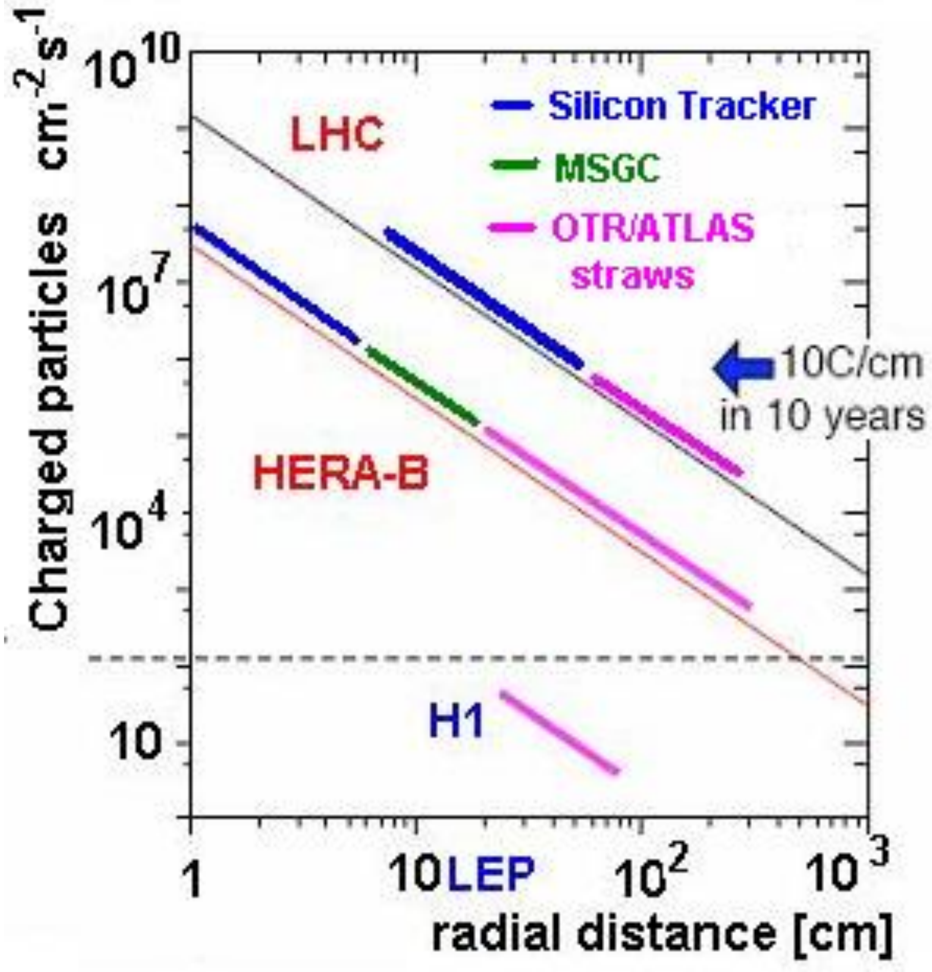


Multi Wire Proportional Chambers MWPC
Time Projection Chambers
Time Expansion Chambers
Proportional Chambers
Thin Gap Chambers
Drift Chambers
Jet Chambers
Straw Tubs
Micro Well Chambers
Cathode Strip Chambers
Resistive Plate Chambers
Micro Strip Gas Chambers
GEM - Gas Electron Multiplier
Micromegas – Micromesh Gaseous Structure

…

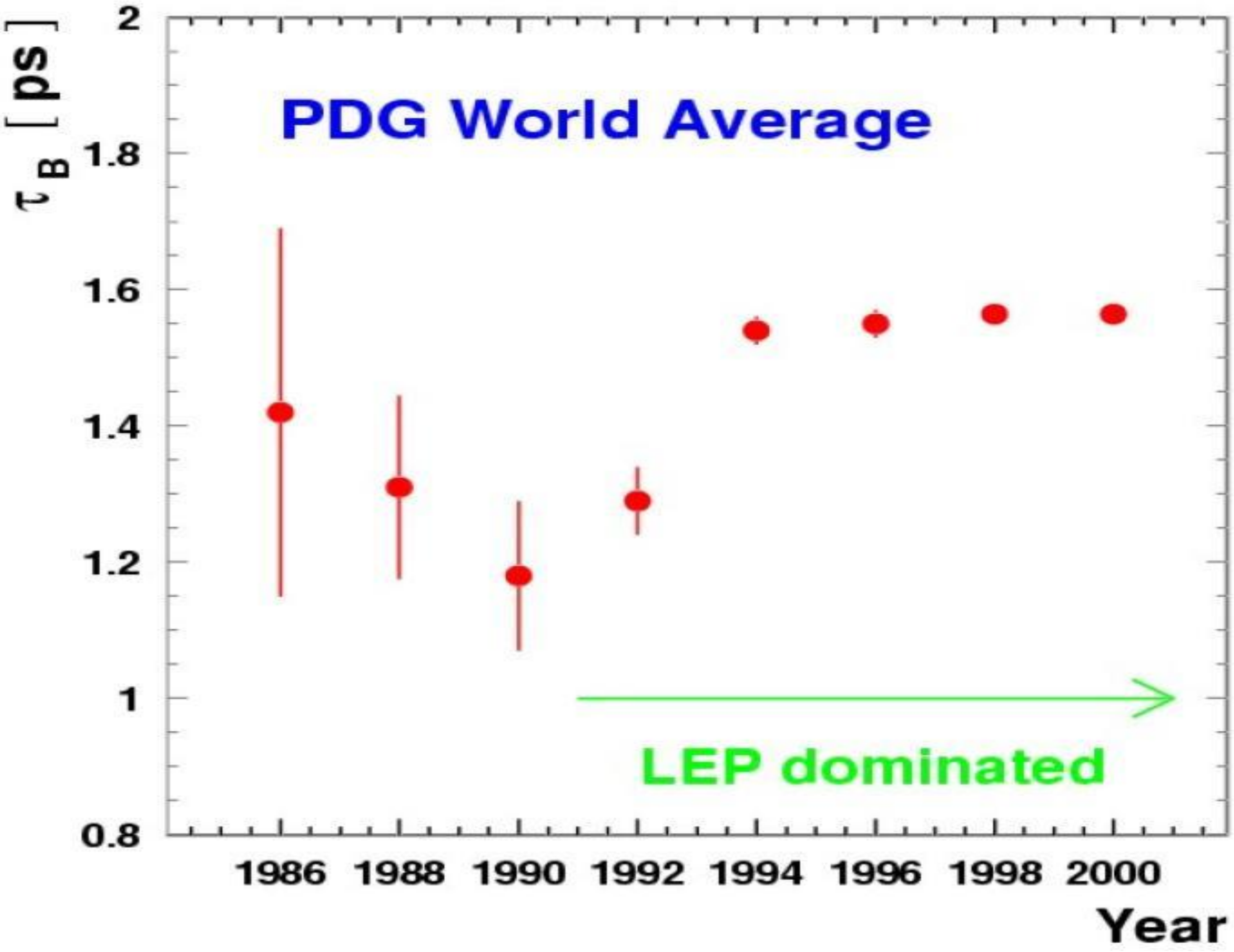
O. Ullaland

Silicon detectors (vertices and precise tracking), examples



Silicon detectors

Traditio
Gas Det
Emulsio
Silicon St

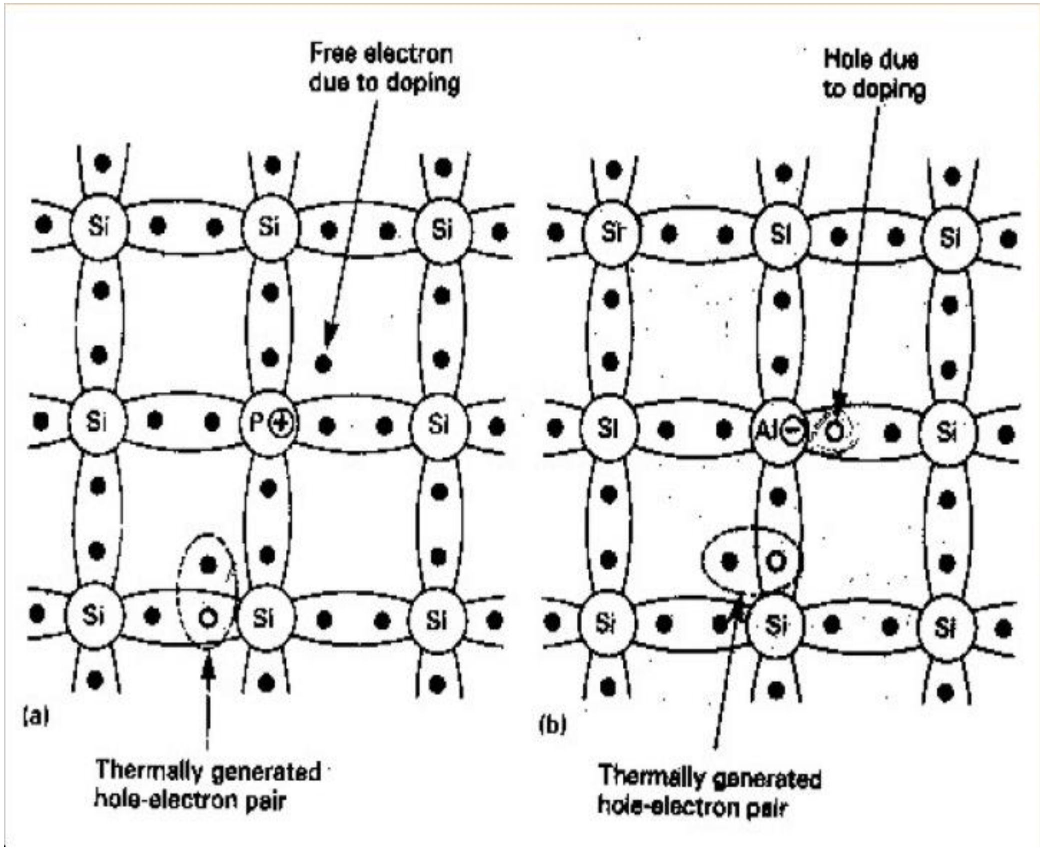


h rates
triggering
Yes
No
Yes

Doping of semiconductors

<u>n-Type</u>
P, As, Sb
5 electrons in the M-shell
1 electron with binding energy 10-50 meV

<u>p-Type</u>
B, Al, Ga
3 electrons in the M-shell
1 electron missing



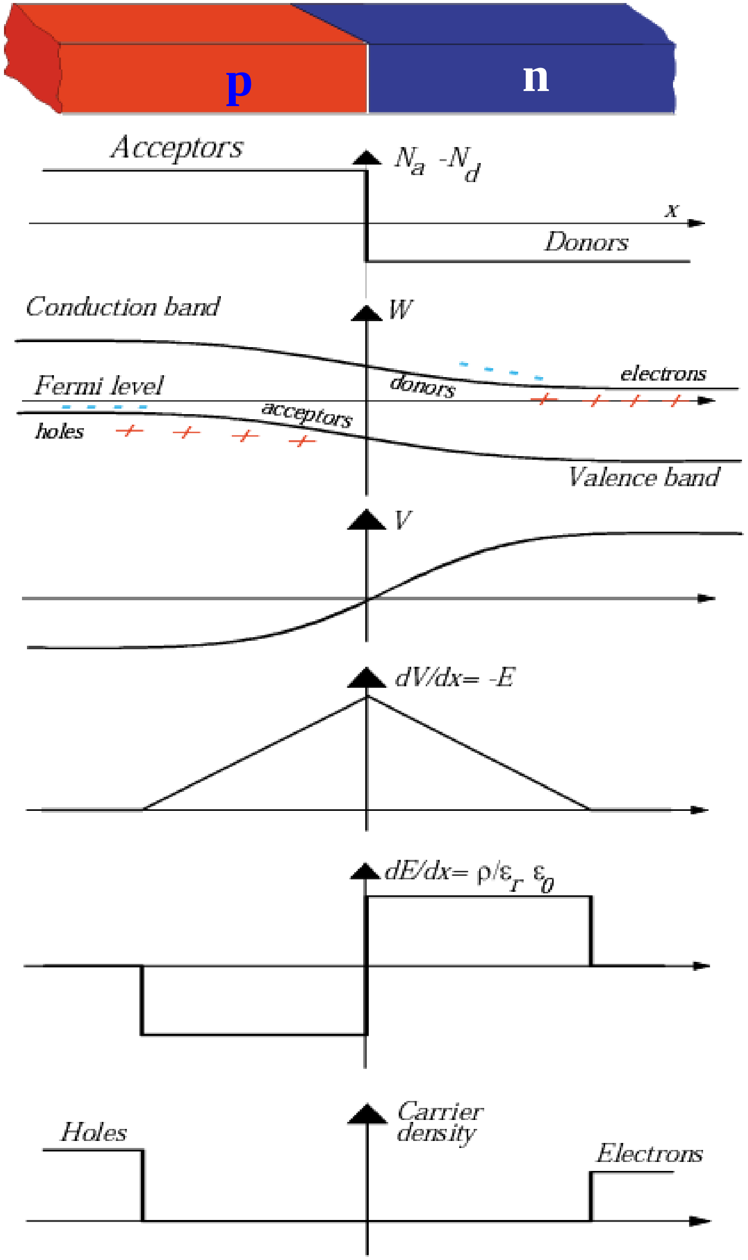
Phosphorus doping: electrons are majority carriers
Boron doping: holes are majority carriers

Some numbers:

Intrinsic carriers: 10^{10}cm^{-3}

Doping concentration: 10^{12}cm^{-3}

Silicon Density: $5 \times 10^{23}\text{cm}^{-3}$



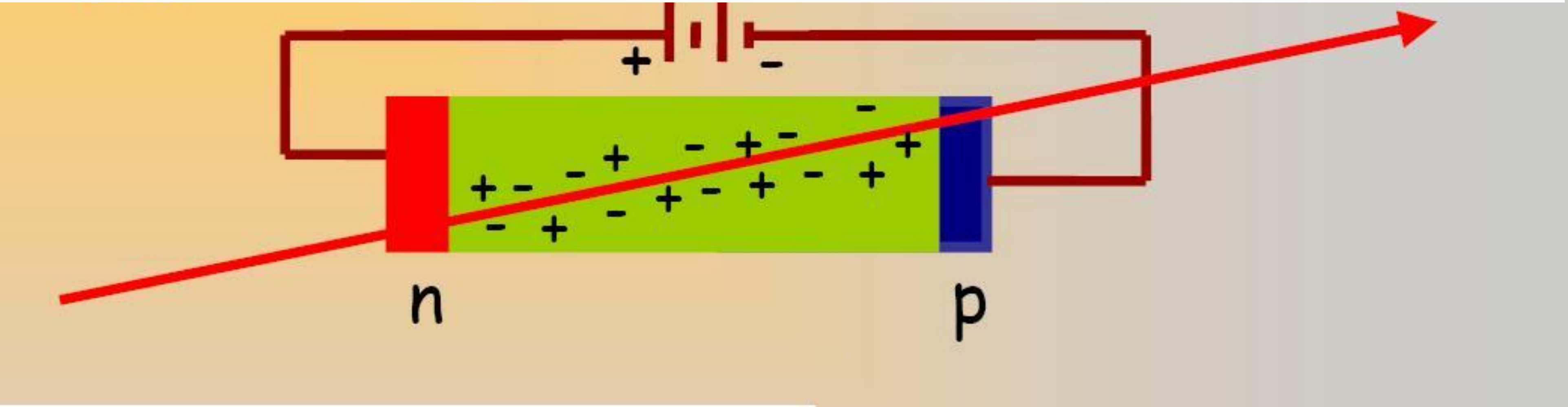
A p-n junction without bias

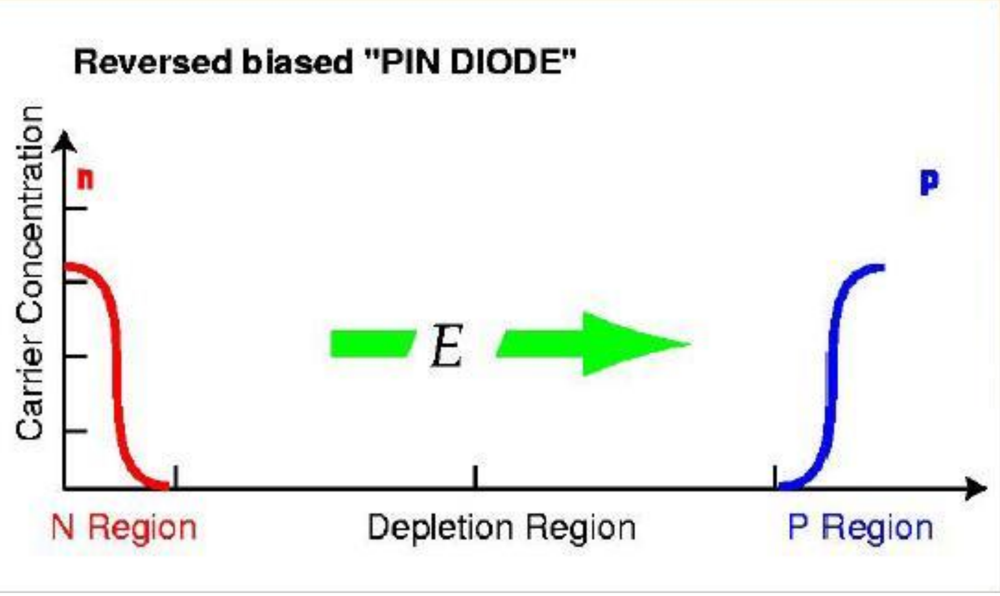
- Peak electric field at the boundary between the p and the n.

- Clear depletion layer.

D. A. Fraser, The physics of semiconductor devices

Apply a reverse bias to extend the depleted region

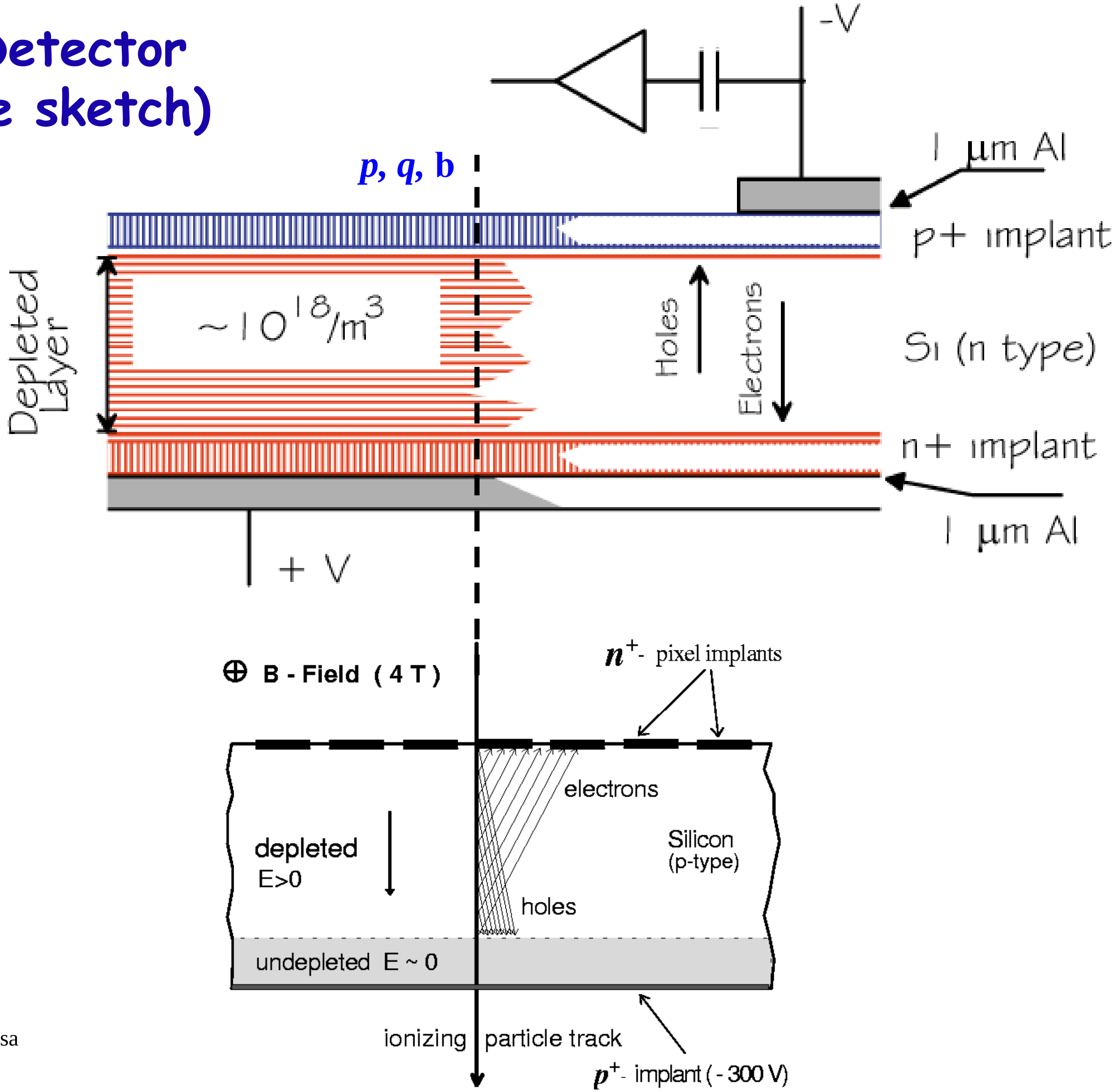




Electron-hole pairs created
By the traversing particle
drift in the electric field

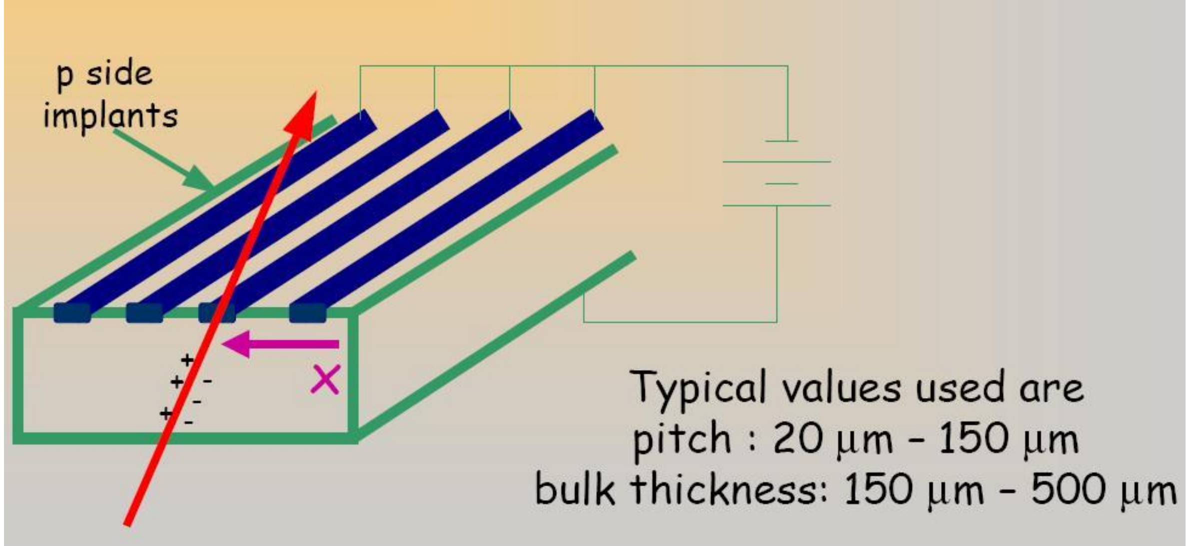
- Energy to create e-h pair ~3.6 eV (30 eV for gas detectors)
- MIP gives ~108 e-h pairs /μm

Silicon Detector (principle sketch)



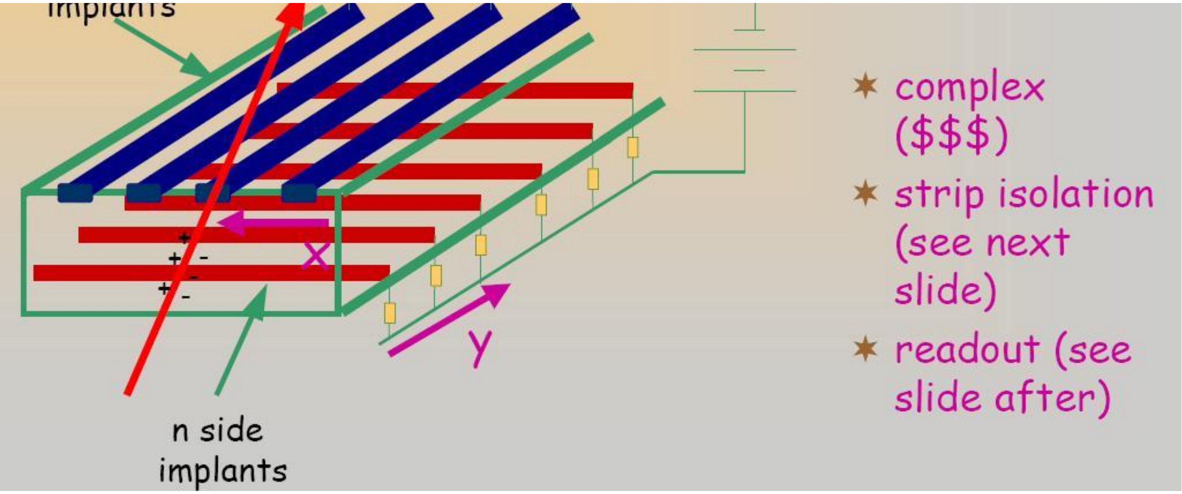
H. Pernegger - CERN
G. Bagliesi - INFN Pisa

Measure coordinate => strips



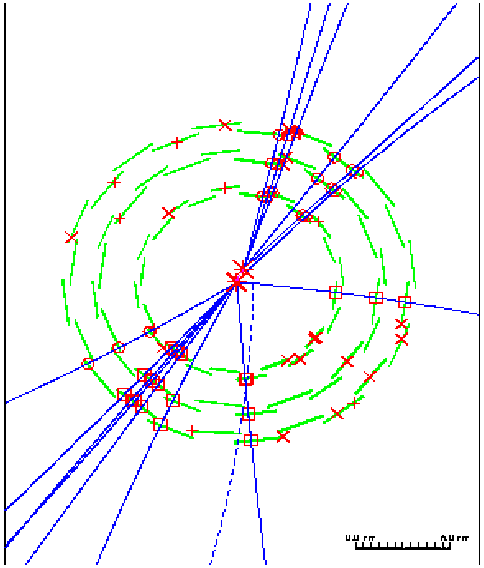
Typical values used are
pitch : 20 µm - 150 µm
bulk thickness: 150 µm - 500 µm

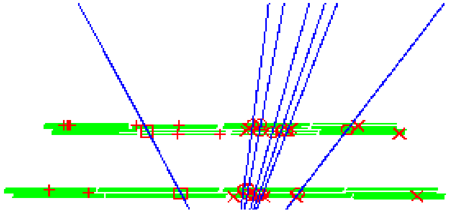
Strips on both sides => 3D measurement

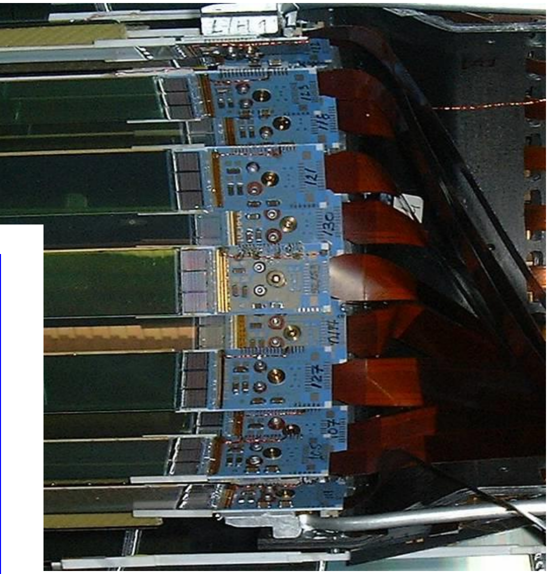


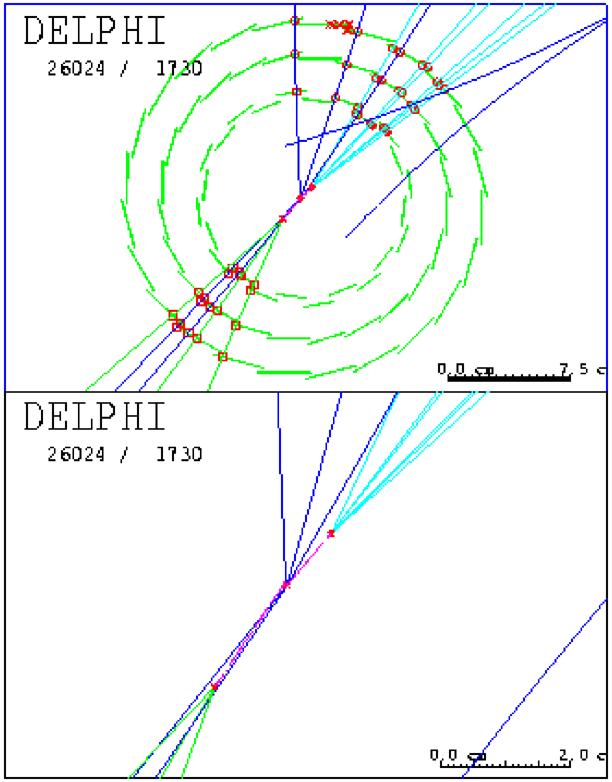
- complex ($$$)
- strip isolation (see next slide)
- readout (see slide after)

Overlapping strips: DELPHI Vertex Detector



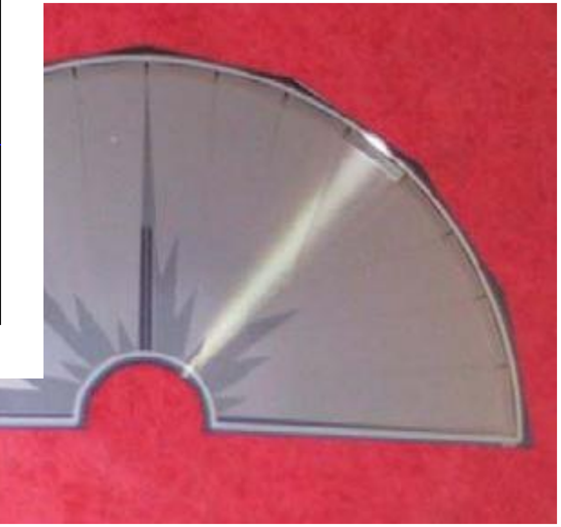






R and

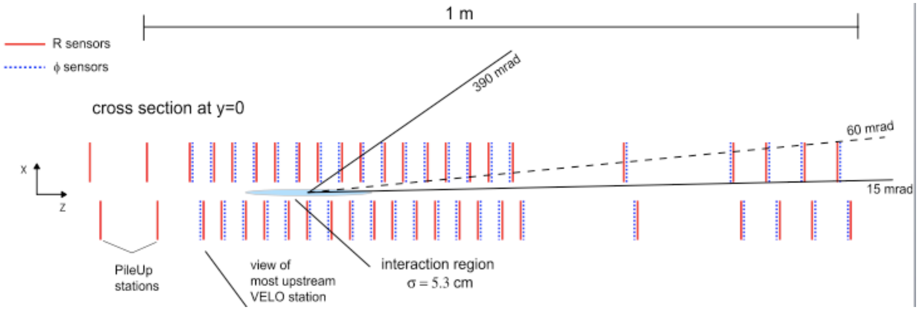
ctor

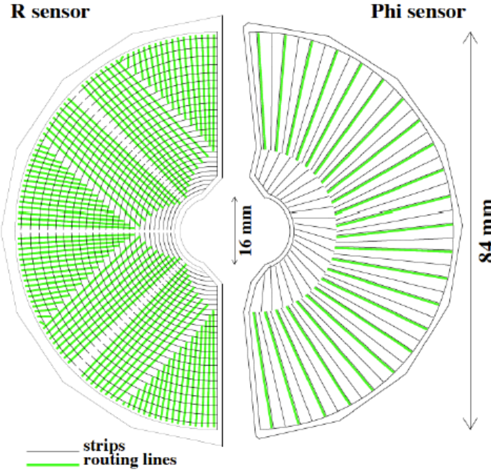


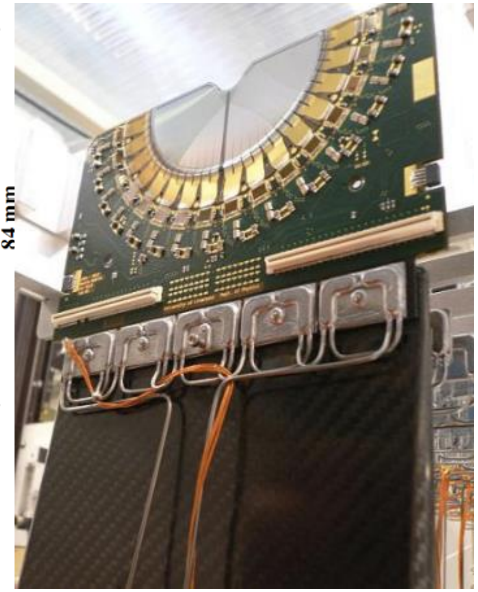
VELO: Vertex LOcator

JINST 8 (2013) P08002, arXiv:1405.7808

- 88 semi-circular microstrip Si sensors
- Double-sided, R and φ layout, in each module
- 300μ thick n-on-n sensors
- Strip pitches from 40 to 120μ







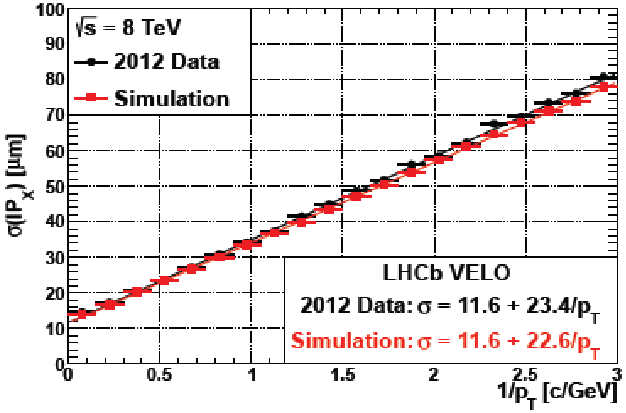
- First active strip at 8.2mm from the beam axis
- Moves away every fill and centers around the beam with self measured vertices

VELO: precise reconstruction of tracks and vertices

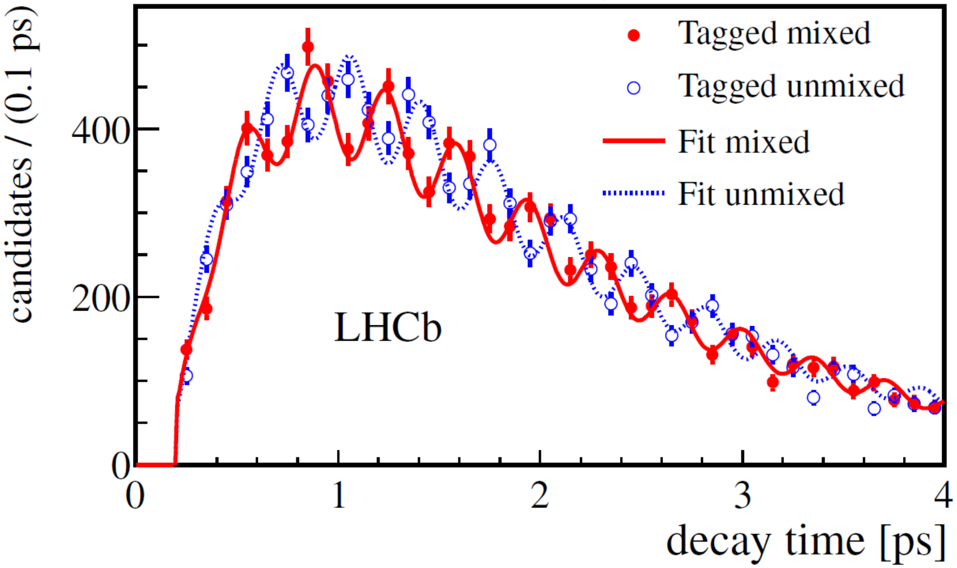
- Excellent spatial resolution, down to 4μ for single tracks
- Precise impact parameter measurement,
  $$\sigma_{IP} = 11.6 + 23.4/pT \quad [\mu]$$
- Precise primary vertex reconstruction,
  $\sigma_x = \sigma_x = 13\mu$, $\sigma_z = 69\mu$ for a vertex of 25 tracks
- Detector well understood, simulation describes data
- VELO provides excellent proper time resolution

Int.J.Mod.Phys. A30 (2015) 1530022

Impact parameter resolution



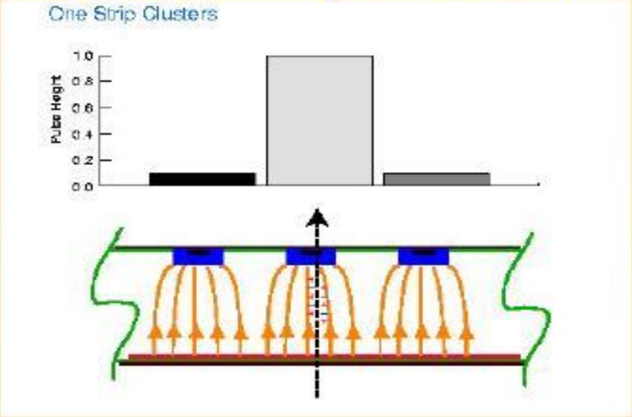
New J. Phys. 15 (2013) 053021



- Vertex resolution allows to resolve fast (x~27) $B_s\bar{B}_s$ oscillations

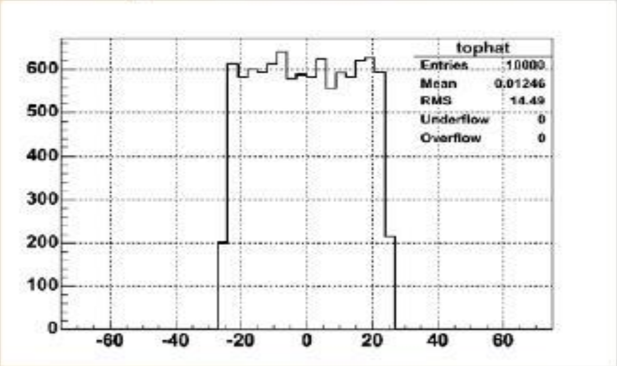
Resolution is the spread of the reconstructed position minus the true position

For one strip clusters

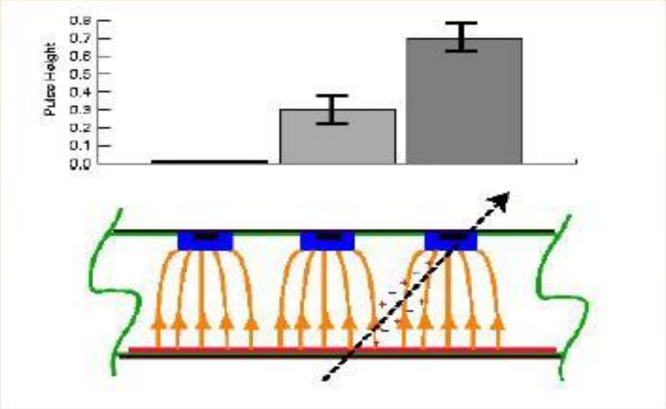


$$\sigma = \frac{\text{pitch}}{\sqrt{12}}$$

"top hat" residuals

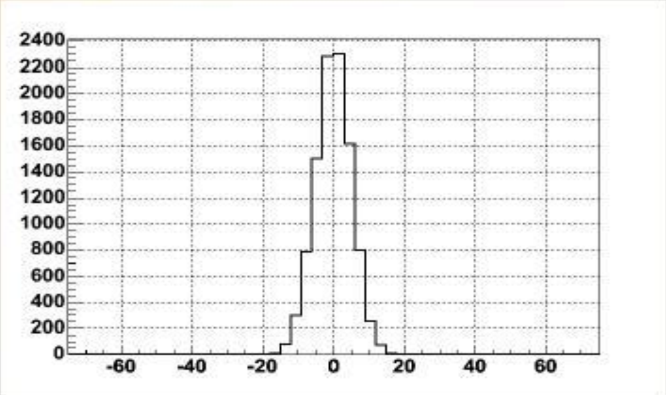


For two strip clusters



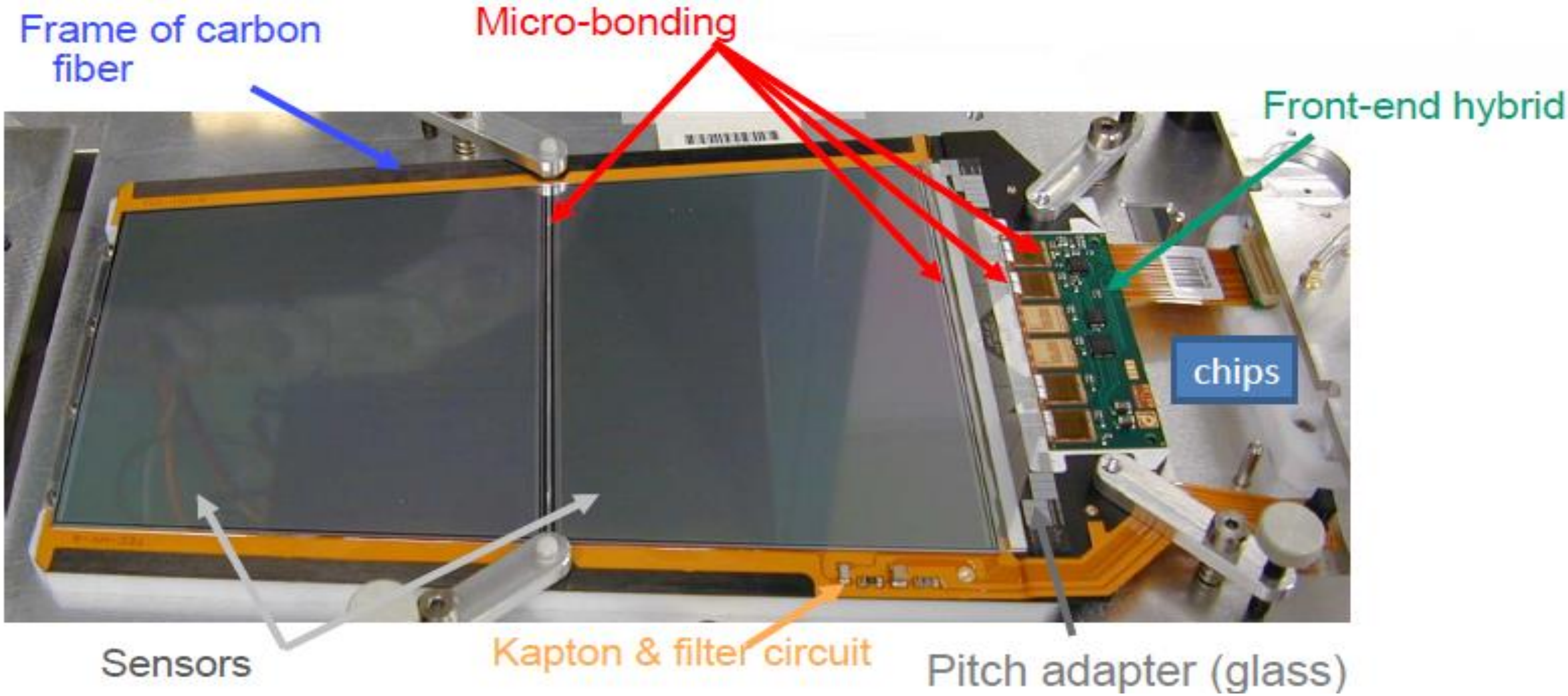
$$\sigma \approx \frac{\text{pitch}}{1.5 * (S/N)}$$

"gaussian" residuals



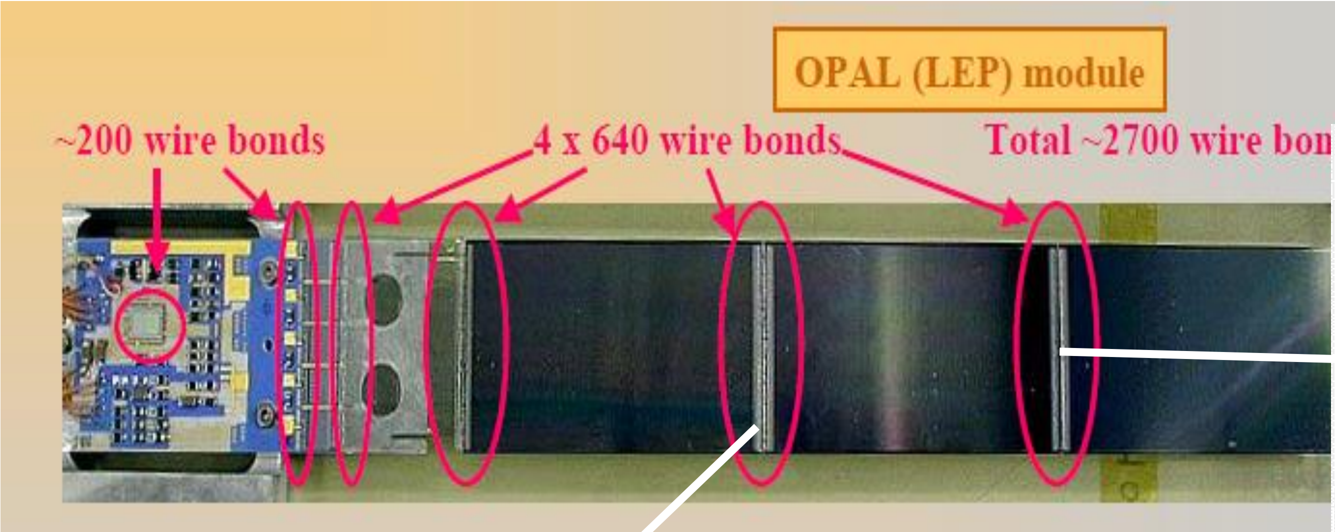
- ❑ In practice, resolution degraded by many factors: relation between pitch and diffusion (typically 25-150 mum and 5-10 mum), statistical fluctuations of energy deposit, …

Si-detector module

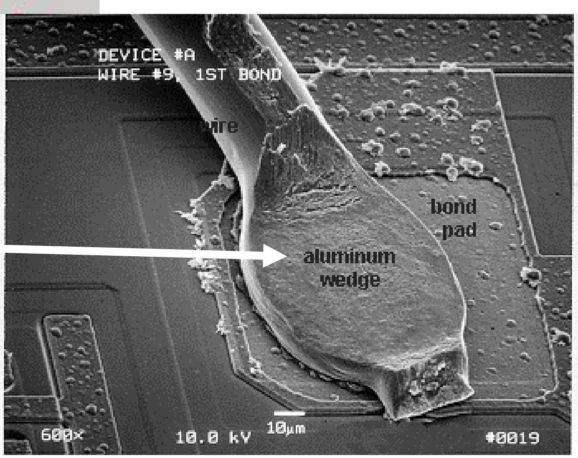


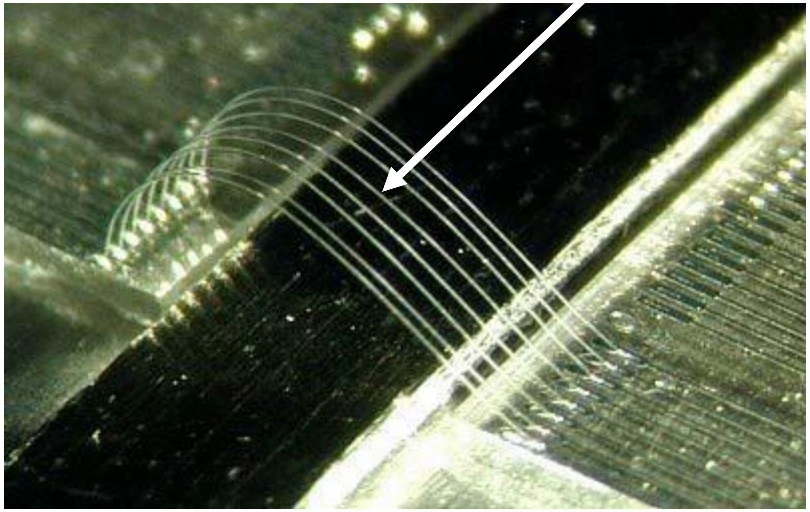
Front-end electronics and connectivity: wire bonding

Wire bonding – A "mature" technology (has been around for 40 years) → conventional technique for connecting sensors to each other and to the front-end chips.



SEM Image of bond "foot":

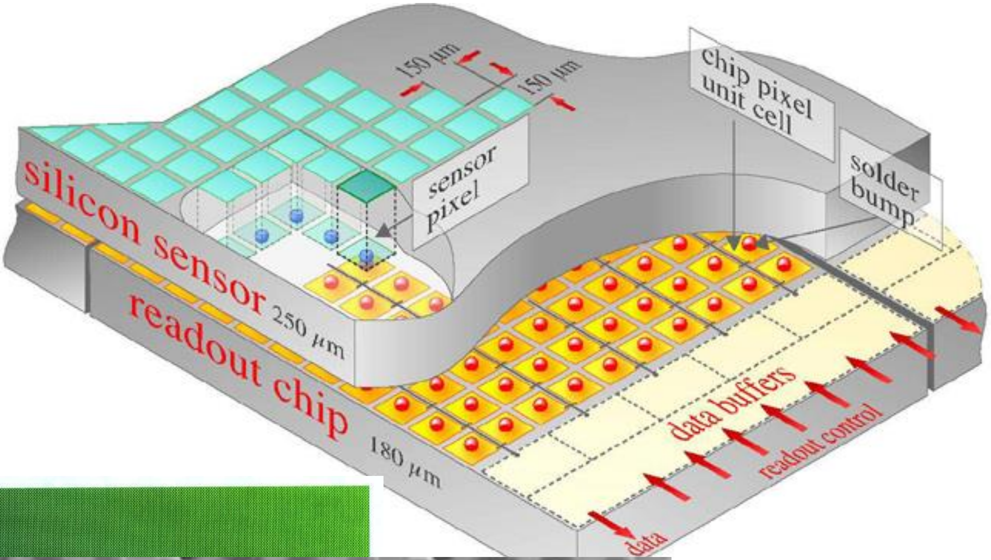




- Uses ultrasonic power to vibrate needle-like tool on top of wire (17-25 um Al wire). Friction welds wire to metalized substrate underneath.

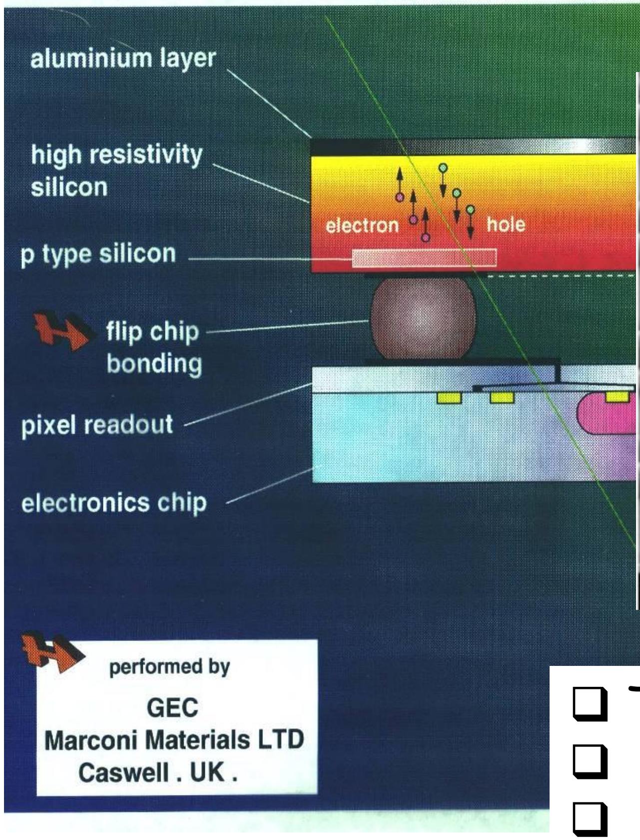
- Heavily used in industry (PC processors) but not with such thin wire or small pitch.

From strips to pixels

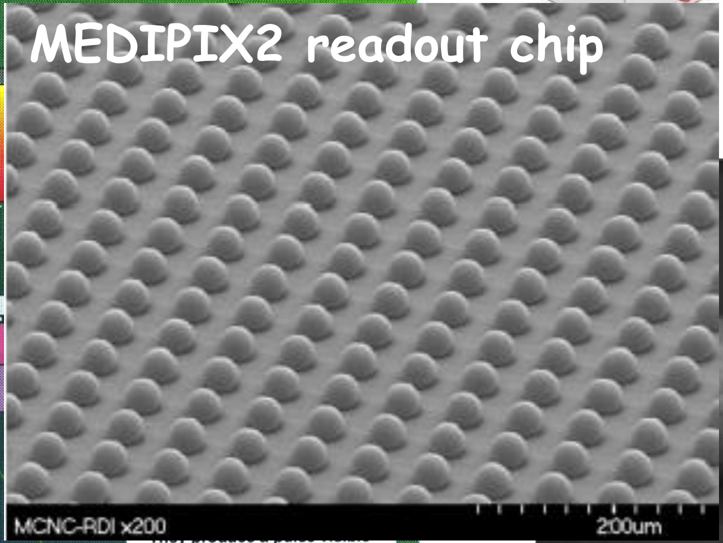


Flip-chip assembly

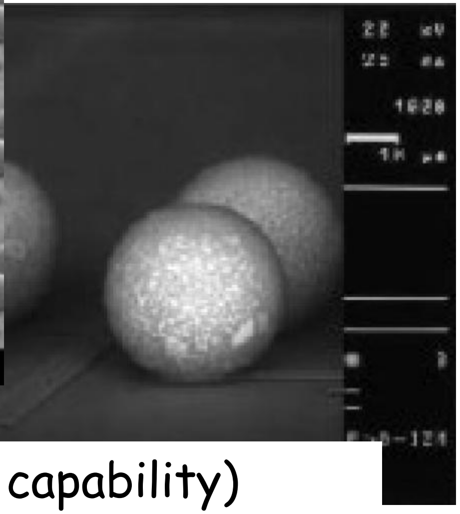
Pixel detector bump bonded to a read-out chip



to the readout electronics .



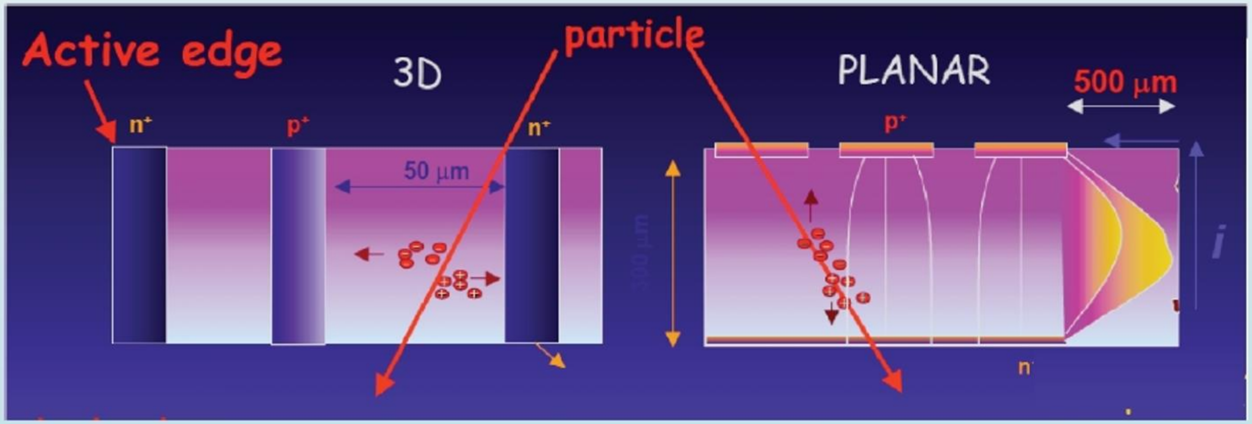
PbSn or In, 6-20 µm
~3000/chip, ~50000/module, …



- ❑ Truly 2D event image (high rate capability)
- ❑ High granularity of readout plane (~50 mum)
- ❑ No long signal routine lines (low noise)

Advanced concepts: 3D Silicon Sensors

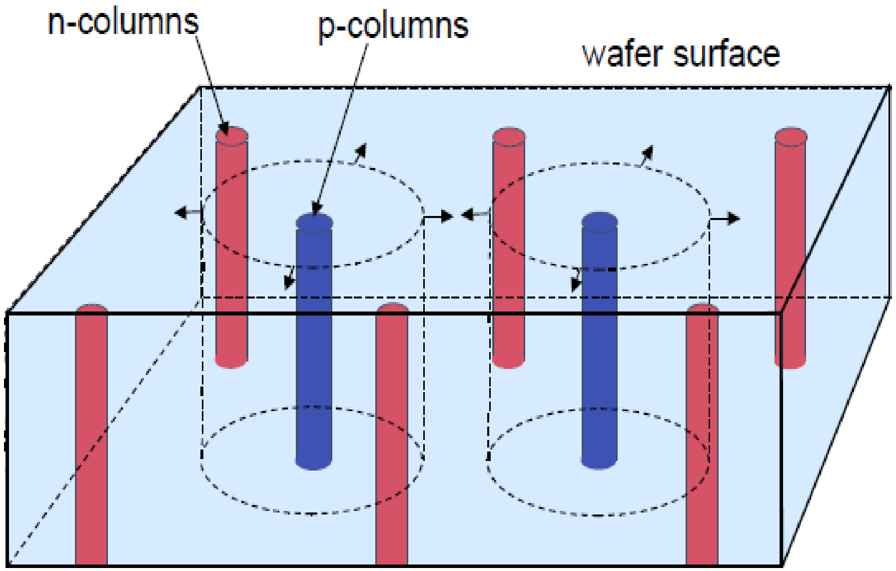
- Challenges for tracking at the future LHC upgrade (sLHC) → current planar-Si sensors technology is not radiation hard to survive to the end of sLHC in the inner layers (R ~ 4 cm)



C. Da Via et al, Nucl. Instr. and Meth. A509(2003)86

- Very small depletion & drift distances:

  hole diameter: 10 μm
  distance ~20-50 μm



- Maximum drift and depletion distance governed by electrode spacing:

- Lower depletion voltages
- Faster/more efficient charge collection
- Small leakage currents
- Higher radiation hardness
- Narrow dead regions at the edges

→ At the price of more complex processing

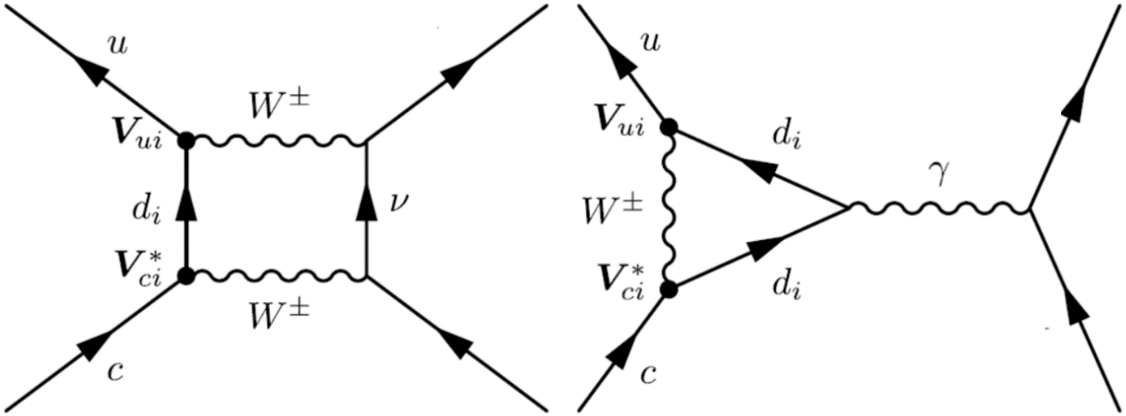
With that we are at **the end** of (fast) lecture series on instrumentation.

You are supposed to retain from these lectures :

- ☐ Instrumentation by itself is a fascinating area
- ☐ However, instrumentation is a tool, it should be considered only in view of a given physics task
- ☐ Conceptual comprehension of the instrumentation is essential even for a theorist ☺
- ☐ There is a big variety of techniques for each method … the choice is often modulated by optimization of performance-background_conditions-reliability-…-cost
- ☐ Complex detector is often designed for many physics tasks, detector choice is sometimes a compromise between their requirements
  - → requires cross-detector optimization
    e.g. : tracking precision vs. material in front of calorimeter
  - → requires often detailed simulation, and always understanding/experience of physics analysis and instrumentation techniques
  - → requires often simultaneous optimization of the whole chain :
    detector – front-end electronics – trigger/readout
- ☐ Despite increasing complexity of detector systems, you can still have a pleasure working on it, and there is still much room for your new bright ideas

Q

Propose an experiment to search for the process $D^0 \rightarrow e^+e^-$



- ☐ Very rare decay, FCNC
- ☐ In SM: BR up to 10^{-13}
- ☐ R-parity violation: BR up to 10^{-12}
- ☐ Experiment: BR < 7.9×10^{-8} @ 90% CL